ENG-005 Renewable Power, Heating&Cooling

Prof. Dr. Michael Hartmann

Recommended Literature

G. Boyle, Renewable Energy – Power for a Sustainable Future, The Open University, Oxford University Press 2007, UK

Planning and Installing Photovoltaic Systems, Deutsche Gesellschaft für Sonnenenergie (DGS), Earthscan, Oxford, UK

V. Quaschning, Understanding Renewable Energy Systems, Earthscan 2010, UK

J. Andrews & N. Jelley, Energy Science – Principles, Technologies and Impacts, third edition, Oxford University Press 2017, New York

M. Kaltschmitt, W. Streicher, A. Wiese, Renewable Energy – Technology, Economics and Environment, Springer 2007, Berlin, Heidelberg, New York

A. Smets, A. Jäger, O. Isabella, R. van Swaaij, M. Zemann, Solar Energy, UIT Cambridge Ltd. 2016, England

Syllabus Part I

01 – Introduction

02 – Solar Radiation and Energy

03 – How Solar Cells Work

04 – Photovoltaic Technologies

05 – Electrical Properties of Solar Cells and Modules

06 – Types of Photovoltaic Installations

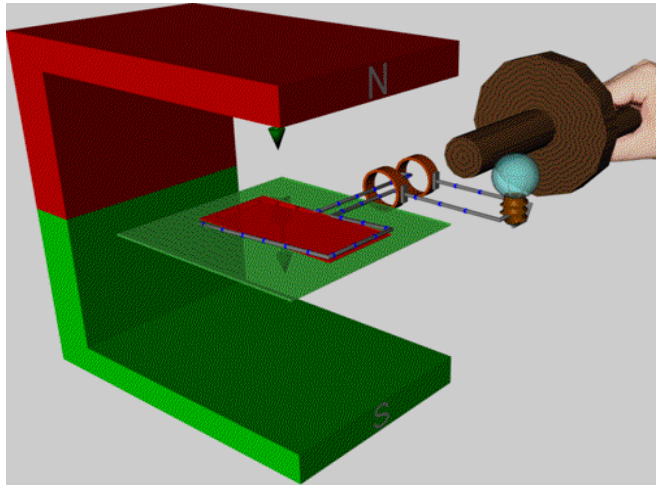
Introduction

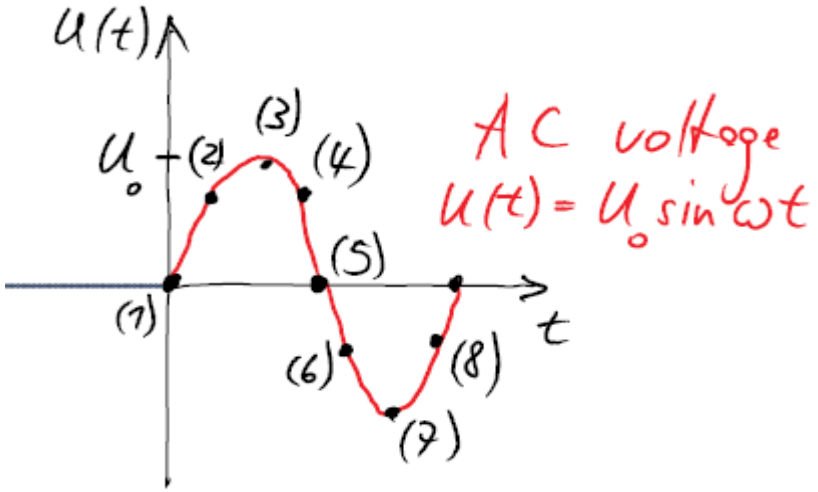
01

Introduction

Typically, electric power is generated by harnessing the Faraday-Maxwell-principle (induction principle or dynamo principle) in electric generators. Simply spoken, when a coil rotates in a magnetic field an electric voltage is induced in the coil. If the generator is integrated into an electric circuit the induced voltage leads to an electric current through the load, e.g. a lamp. Due to the rotation alternate voltage and current (AC) are generated. For the rotational motion, steam is generated driving a turbine. For the steam generation, traditionally burning of fossiles or nuclear power or renewable sources like wind or hydro power can be used.

In contrast, solar energy can be used for direct conversion of solar radiation into electric power (photovoltaics) or for heating purposes (solar thermal power).



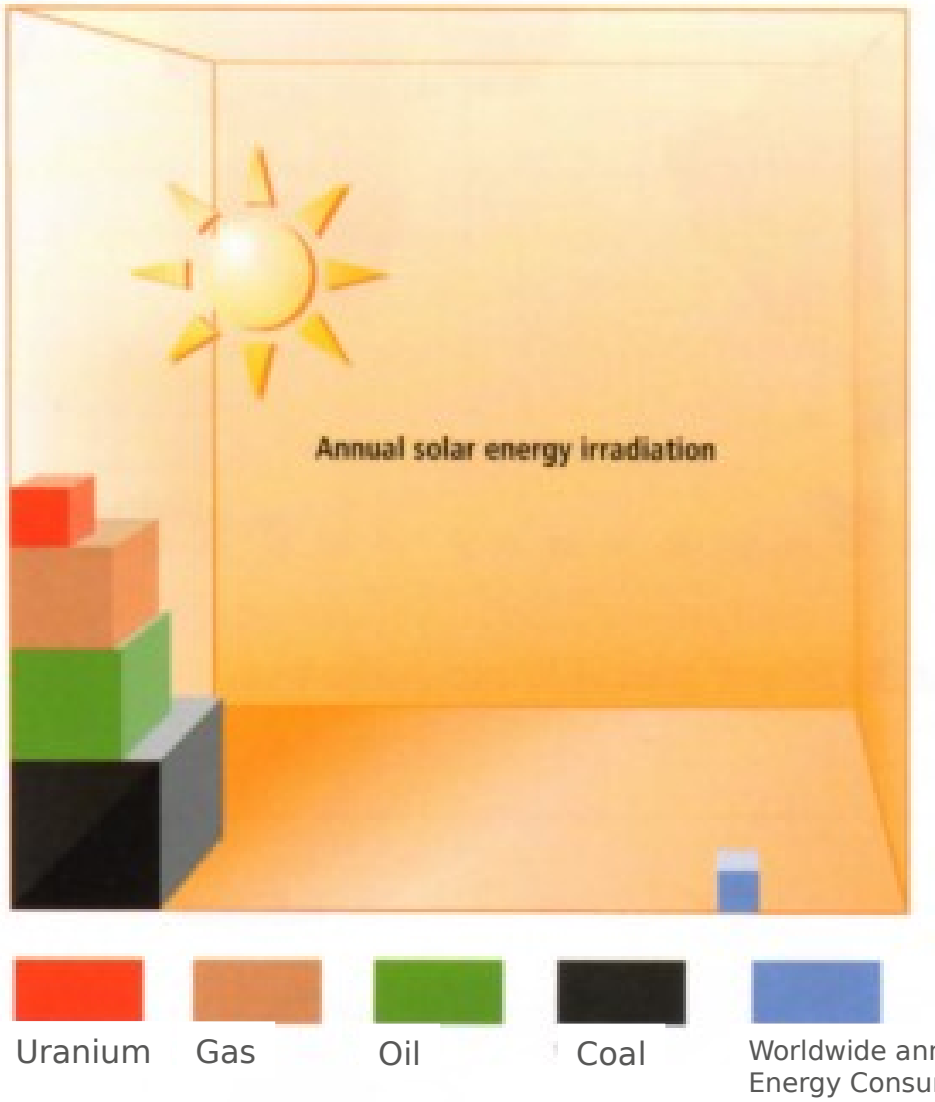


For a simulation see
http://upload.wikimedia.org/wikipedia/commons/e/ec/Dynamo.wechsel.wiki.v.1.00.gif

Solar Radiation and Energy

02

Solar Radiation and –



Annual solar energy in comparison to fossil resources and worldwide annual energy consumption

Source: BMWi 2000

Solar Radiation and Energy

The sun emits electromagnetic radiation which is a wave consisting of electric and the magnetic field components oscillating in space and time. One characteristics of electromagnetic waves is therefore the wavelength (distance between two maxima of the wave) symbolized by **λ** (lambda). The wave is also moving forward in time. The number of maxima passing during a certain time period
(e.g. 1 second) is called frequency symbolized by **ν** (nu- Greek n). The SI- unit of the frequency is 1 Hertz (1Hz) which is the pass-through of 1 maximum in 1 second.

1Hz = 1/s

Example: a frequency of 10 000 Hz means that 10 000 maxima of the electromagnetic wave is passing during 1 second.

Solar Radiation and Energy

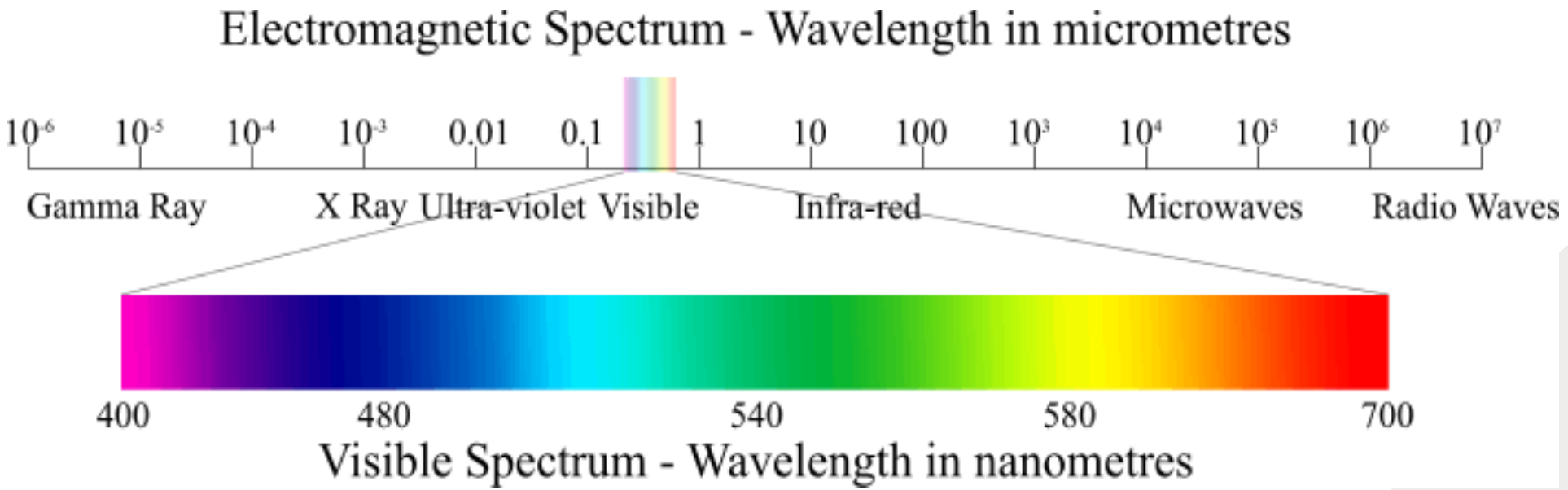
The speed of electromagnetic waves in vacuum is always constant. **c = 300 000 km/s** therefore there is a relation between wavelength **λ** and frequency **ν** given by:

$$c = \lambda \cdot \nu.$$

The wavelength **λ** of electromagnetic waves covers a broad range, from several thousand meter (radio waves) down to some pico meter (10^{-12} m - γ-rays). The corresponding frequencies range from 10^4 Hz (radio waves) until 10^{21}Hz (X- and γ-rays), see next slide. Only a small range between 400 and 750 nm is visible by our eyes.

Solar Radiation and Energy

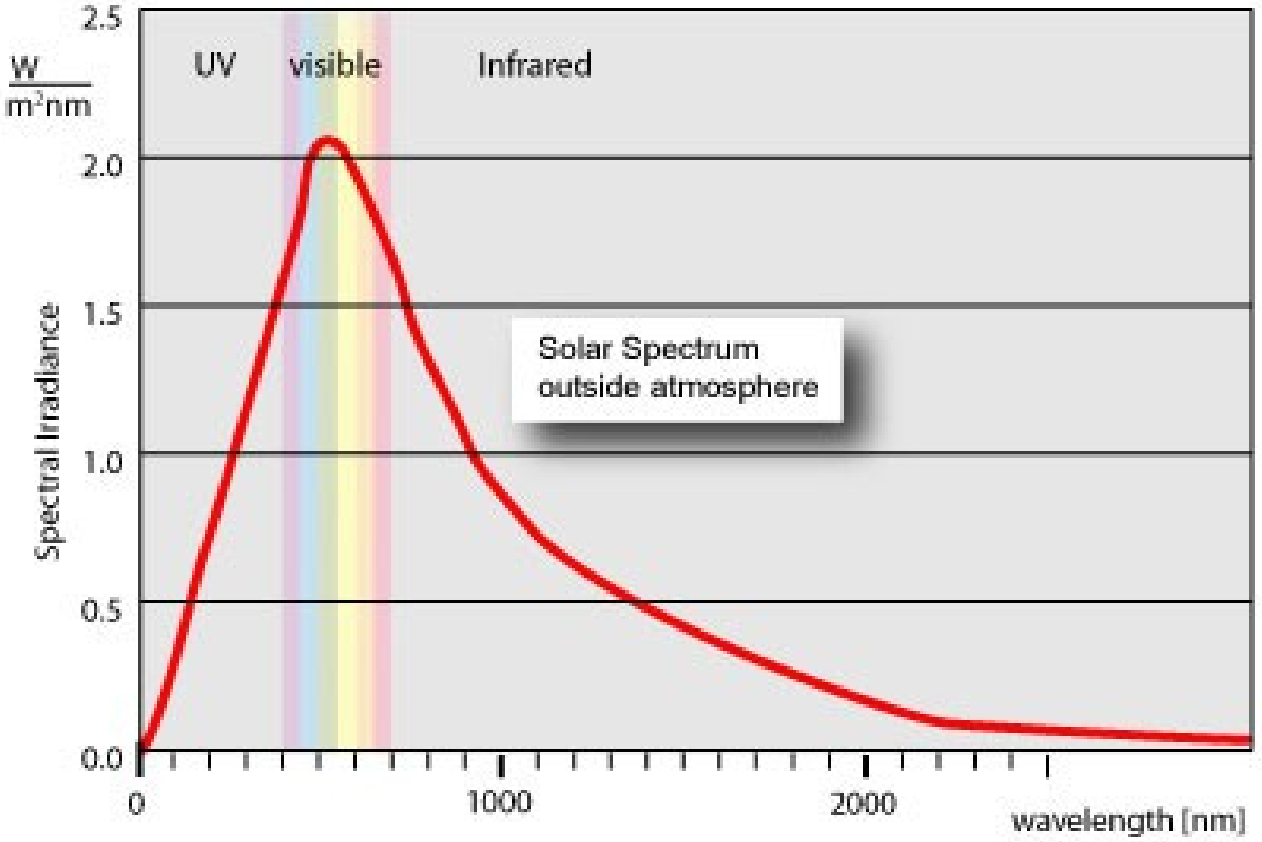
The electromagnetic spectrum cp. to the visible spectrum



Source: http://www.ctahr.hawaii.edu/miuralab/projects/makaha/assets/spectrum.png

Solar Radiation and Energy

Intensity of the different wavelength in the solar spectrum



Source: Green Rhino Energy

Solar Radiation and Energy

The energy of electromagnetic waves is proportional to their frequencies and is written:

$$E = h \bullet \nu = h \bullet c/\lambda$$

Here the proportionality constant h was introduced called Planck's constant in honor of Max Planck (one of the famous scientists of the 20th century). Planck's constant is another fundamental constant of nature and given by

$$h = 6.62607 \bullet 10^{-34}\ \text{Js}$$

Radio waves have lower frequencies and therefore small energies in the order of 10^{-30} J. γ-rays have very high frequencies and hence high energies $\approx 10^{-13}$ J. Both values look very small compared to macroscopic energies, but remember that, e.g. γ-rays can penetrate into the human body and affect the genetic material like the DNA. For DNA molecules which are very tiny, the energy of γ-rays is huge. Therefore, from a molecular or atomic perspective, high frequency radiation or light is felt like "little bombs" and therefore the radiation can be considered to consist of light particles called photons. A beam of radiation or light is therefore a flow of photons (particle – wave dualism).

Since the energy values are so small, a new energy unit in atomic and nuclear physics is introduced, the electron volt

$$1\ \text{eV} = 1.60218\ 10^{-19}\ \text{J}$$

Solar Radiation and Energy

Exercise

Calculate the energy of

a) Red light with a wavelength of 700 nm
b) Green light with a wavelength of 550 nm
c) UV light with a wavelength of 300nm
d) Gamma ray with a frequency of 10^{20}Hz.

Solar Radiation and Energy

Exercise

Calculate the energy of
a) red light with a wavelength of 700 nm

$E = h \cdot c / \lambda = 6.62607 \cdot 10^{-34}\ Js \cdot 300\ 000\ km/s / 700nm$

$= 6.62607 \cdot 10^{-34}\ Js \quad 300\ 000\ 000\ m/s \ / \ 700 \cdot 10^{-9}\ m$

$= 6.62607 \cdot 3 \cdot 10^{-26} / 700 \cdot 10^{-9}\ J$

$= 6.62607 \cdot 3/700 \cdot 10^{-26+9}\ J$

$= 6.62607 \cdot 3/700 \cdot 10^{-17} J$

$= 0.028 \cdot 10^{-17} J = 2.8 \cdot 10^{-19} J$

$= 1.772\ eV$

Solar Radiation and Energy

Exercise

Calculate the energy of
b) green light with a wavelength of 550 nm

$E = h \cdot c/\lambda = 6.62607 \cdot 10^{-34}\,Js \cdot 300\,000\,km/s / 550nm$

$= 6.62607 \cdot 10^{-34}\,Js \;\; 300\,000\,000\,m/s \;/\; 550 \cdot 10^{-9}\,m$

$= 6.62607 \cdot 3 \cdot 10^{-26}/550 \cdot 10^{-9}\,J$

$= 6.62607 \cdot 3/550 \cdot 10^{-26+9}\,J$

$= 6.62607 \cdot 3/550 \cdot 10^{-17} J$

$= 0.036 \cdot 10^{-17} J = 3.6 \cdot 10^{-19} J$

$= 2.247\,eV$

Solar Radiation and Energy

Exercise

Calculate the energy of
c) UV light with a wavelength of 300nm

$E = 6.62607 \cdot 10^{-34}\ Js \cdot\ 3 \cdot 10^{8} m/s\ 300 \cdot 10^{-9} m$
$= 0.066 \cdot 10^{-17} J = 6.6 \cdot 10^{-19} J$
$= 4.119\ eV$

Solar Radiation and Energy

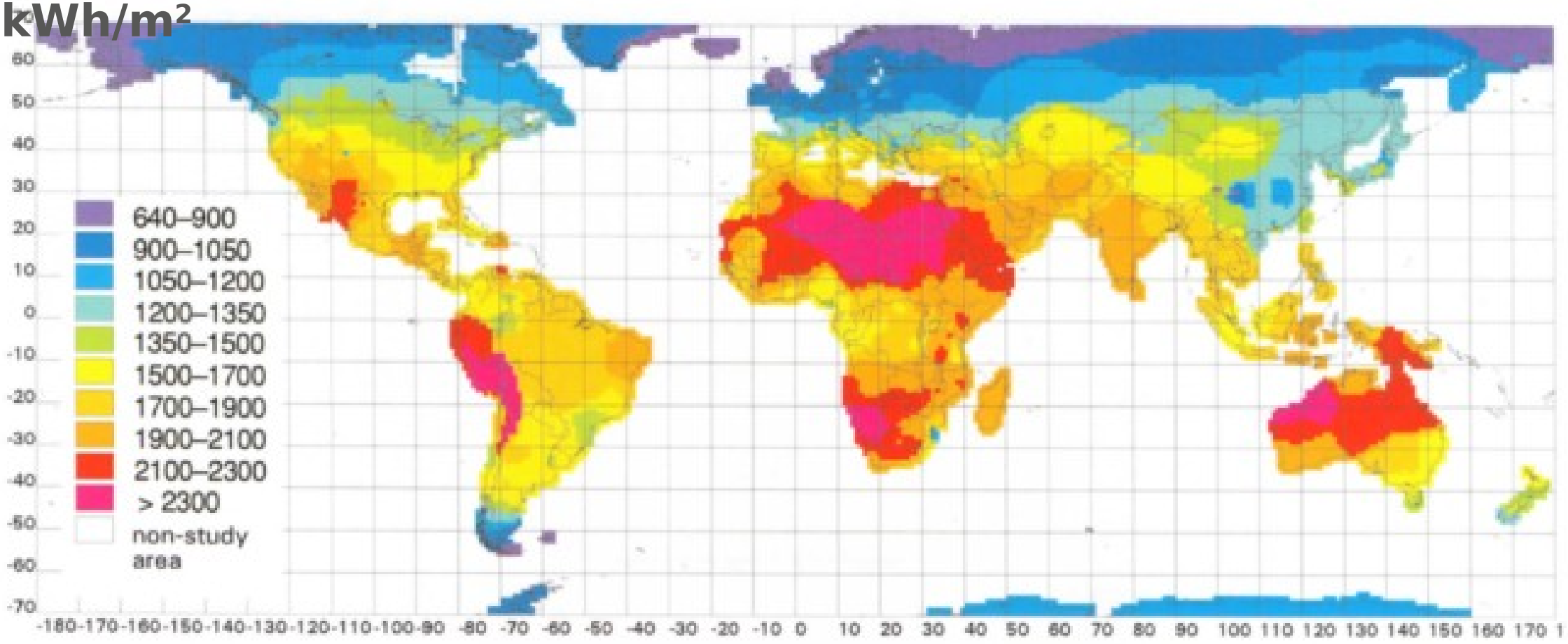
Exercise

Calculate the energy of
d) Gamma ray with a frequency of 10^{20}Hz.

$E = h \cdot \mathbf{v} = 6.62607 \cdot 10^{-34}$ Js $\cdot 10^{20}$ /s
$= 6.62607 \cdot 10^{-14}$ J
$= 4.136 \cdot 10^{5}$ eV

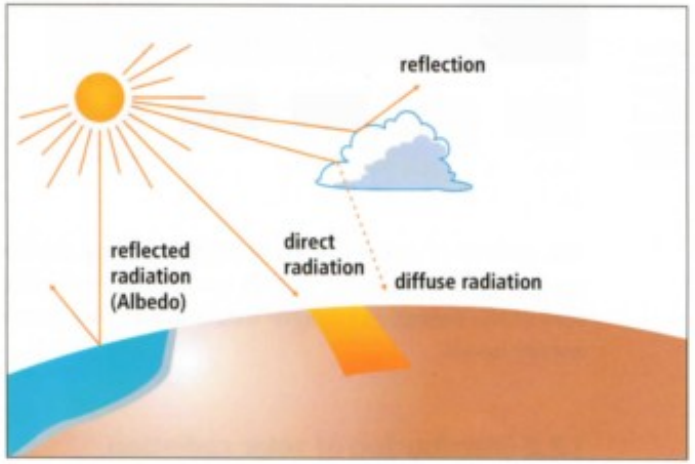
Solar Radiation and Energy

Worldwide distribution of annual solar irradiance in kWh/m²



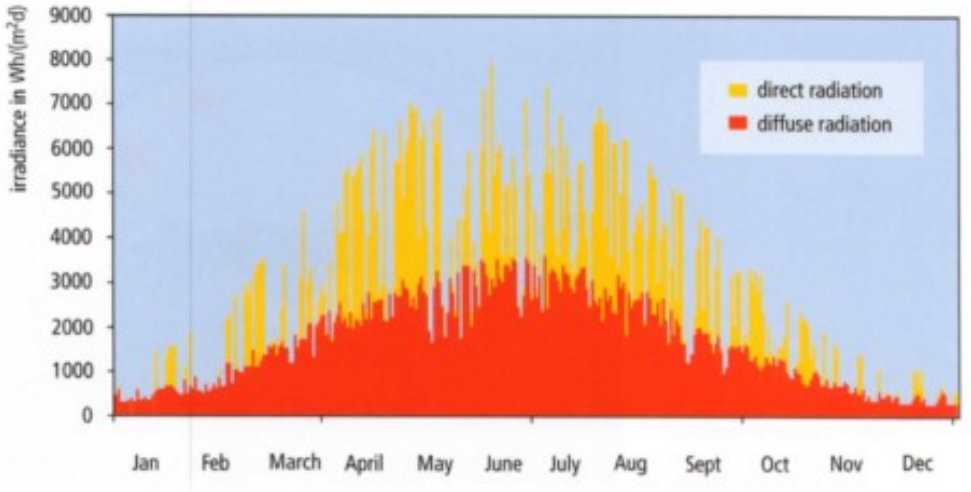
Solar Radiation and Energy

Types of solar radiation

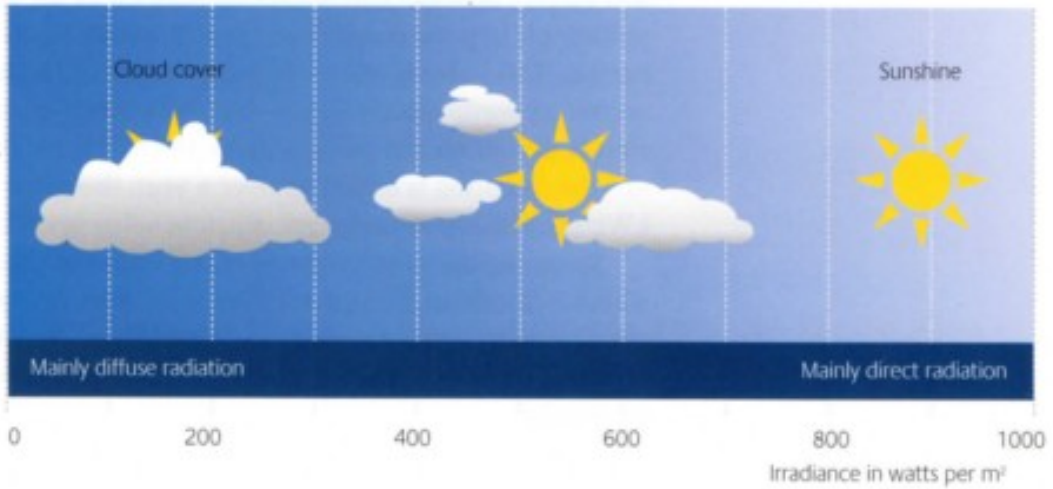


Source: V. Quaschning

Direct and diffuse solar radiation in Berlin

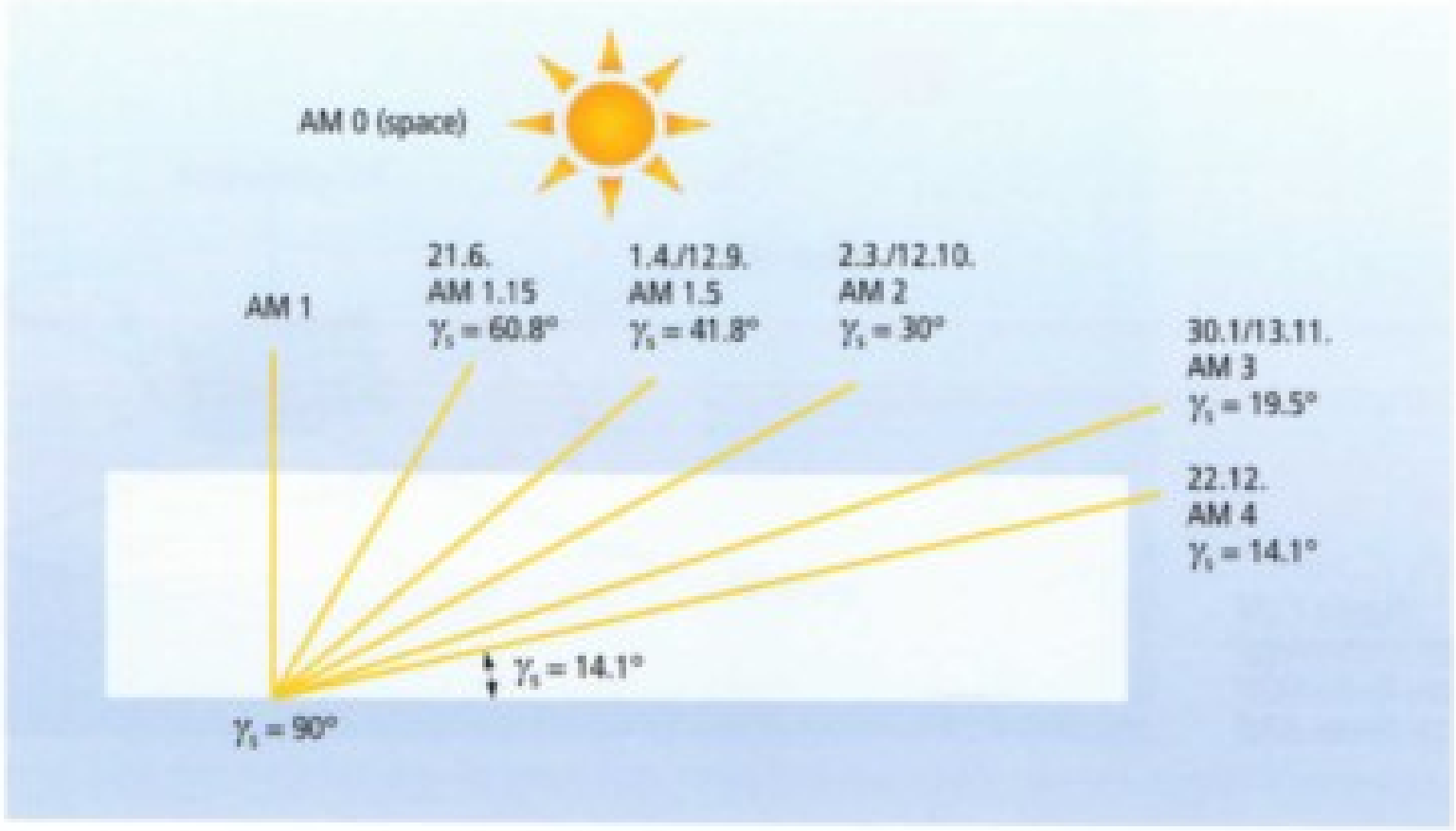


Source: Planning and Installing Photovoltaic



Solar Radiation and Energy

Solar altitude at noon over the course of the year in Berlin



Source: V. Quaschning

Definition: Air Mass

$$AM = \frac{1}{\sin\gamma_S}$$

Solar Radiation and Energy

Atmospheric influence on the solar irradiance

Absorption and different types of scattering in dependence on the sun‘s altitude

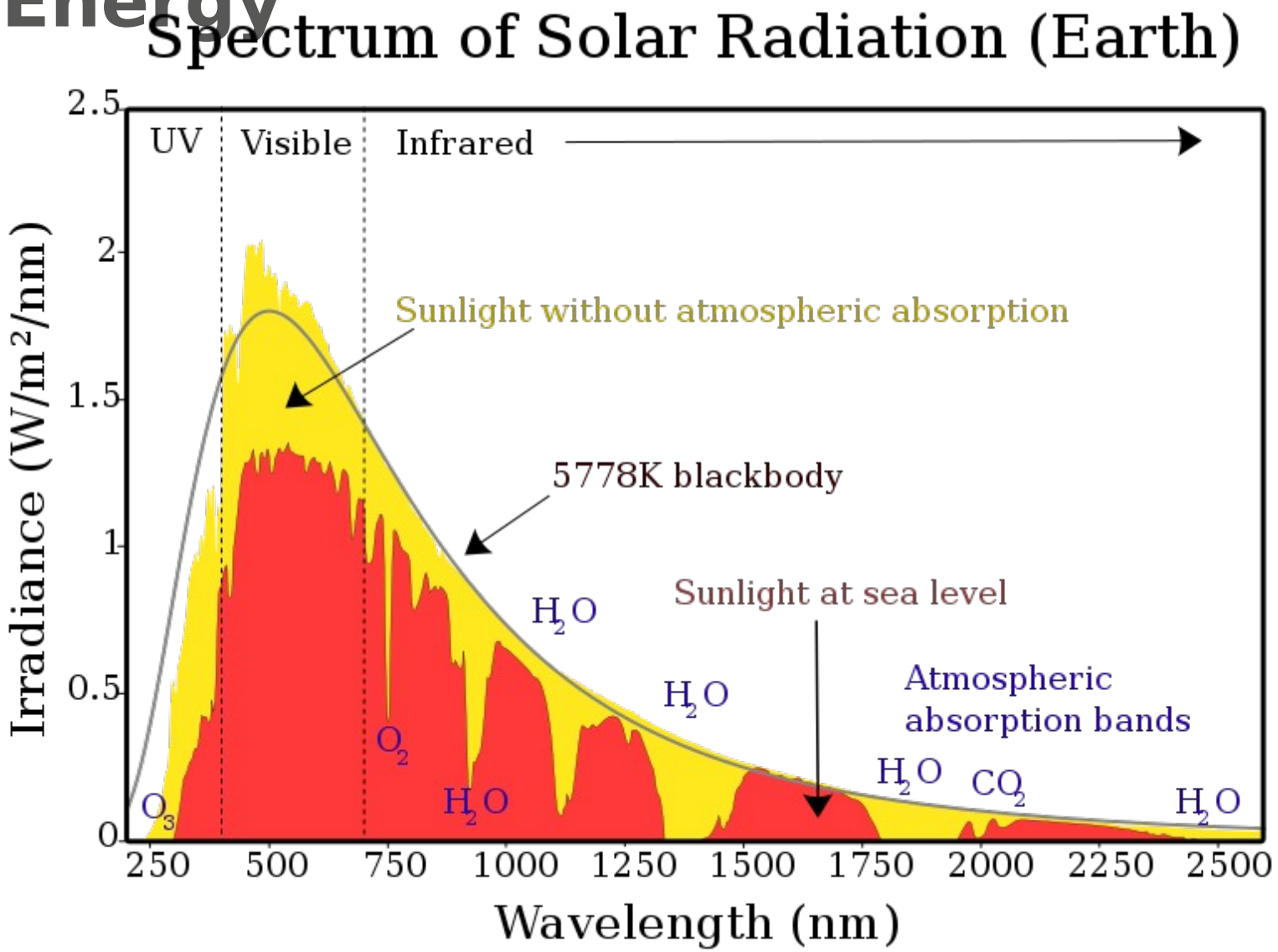
	AM	Absorption	Rayleigh scattering	Mie scattering	Overall reduction
90°	1.00	8.7%	9.4%	0–25.6%	17.3–38.5%
60°	1.15	9.2%	10.5%	0.7–29.5%	19.4–42.8%
30°	2.00	11.2%	16.3%	4.1–44.9%	28.8–59.1%
10°	5.76	16.2%	31.9%	15.4–74.3%	51.8–85.4%
5°	11.5	19.5%	42.5%	24.6–86.5%	65.1–93.8%

Albedo numbers for different environments

Surface	Albedo	Surface	Albedo
Grass (July, August)	0.25	Asphalt	0.15
Lawn	0.18–0.23	Forests	0.05–0.18
Dry Grass	0.28–0.32	Heather and sandy areas	0.10–0.25
Untilled fields	0.26	Water surface (γ_s > 45°C)	0.05
Barren soil	0.17	Water surface (γ_s > 30°C)	0.08
Gravel	0.18	Water surface (γ_s > 20°C)	0.12
Clean concrete	0.30	Water surface (γ_s > 10°C)	0.22
Eroded concrete	0.20	Fresh layer of snow	0.80–0.90
Clean cement	0.55	Old layer of snow	0.45–0.70

Source: Planning and Installing Photovoltaic Systems

Solar Radiation and Energy



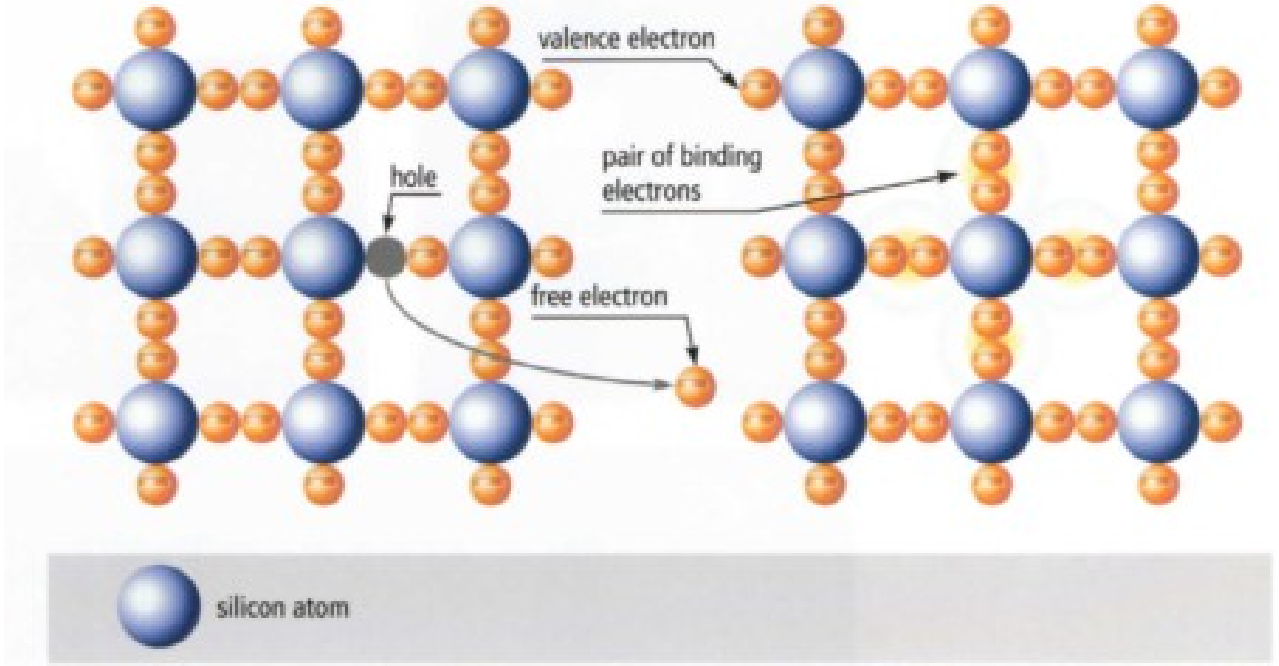
How Solar Cells Work

03

How Solar Cells Work

Photovoltaic technology applies semiconducting materials to convert solar radiation **directly** into electric power. How does this work?

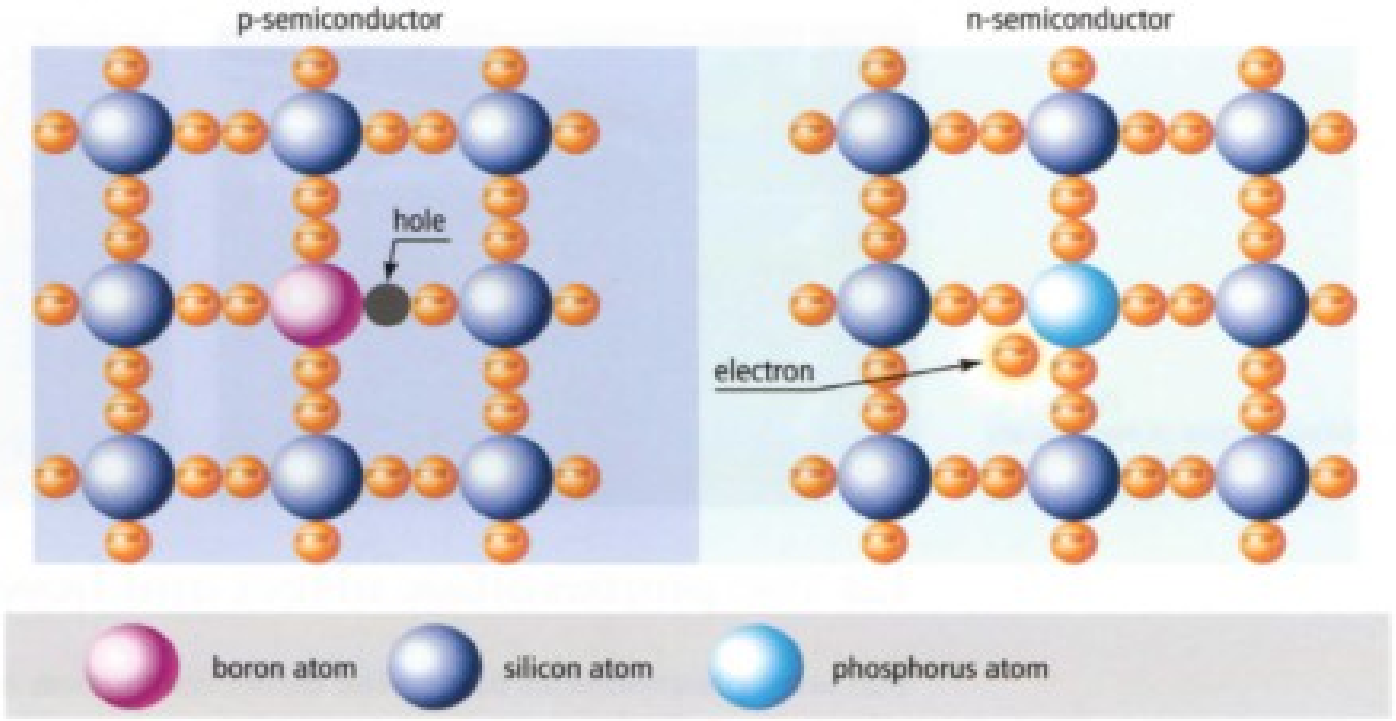
Semiconductors like silicon have a crystalline structure created by the interaction of the four valence electrons of a silicon atom with the neighboring atom. The negatively charged valence electrons are relatively weakly bound to its core and therefore, statistically due to thermal motions, a certain amount of electrons move through the crystal causing a so called **intrinsic conductivity**. Doing so, the negatively charged electrons leave a positively charged hole behind.



Source: V. Quaschning

How Solar Cells Work

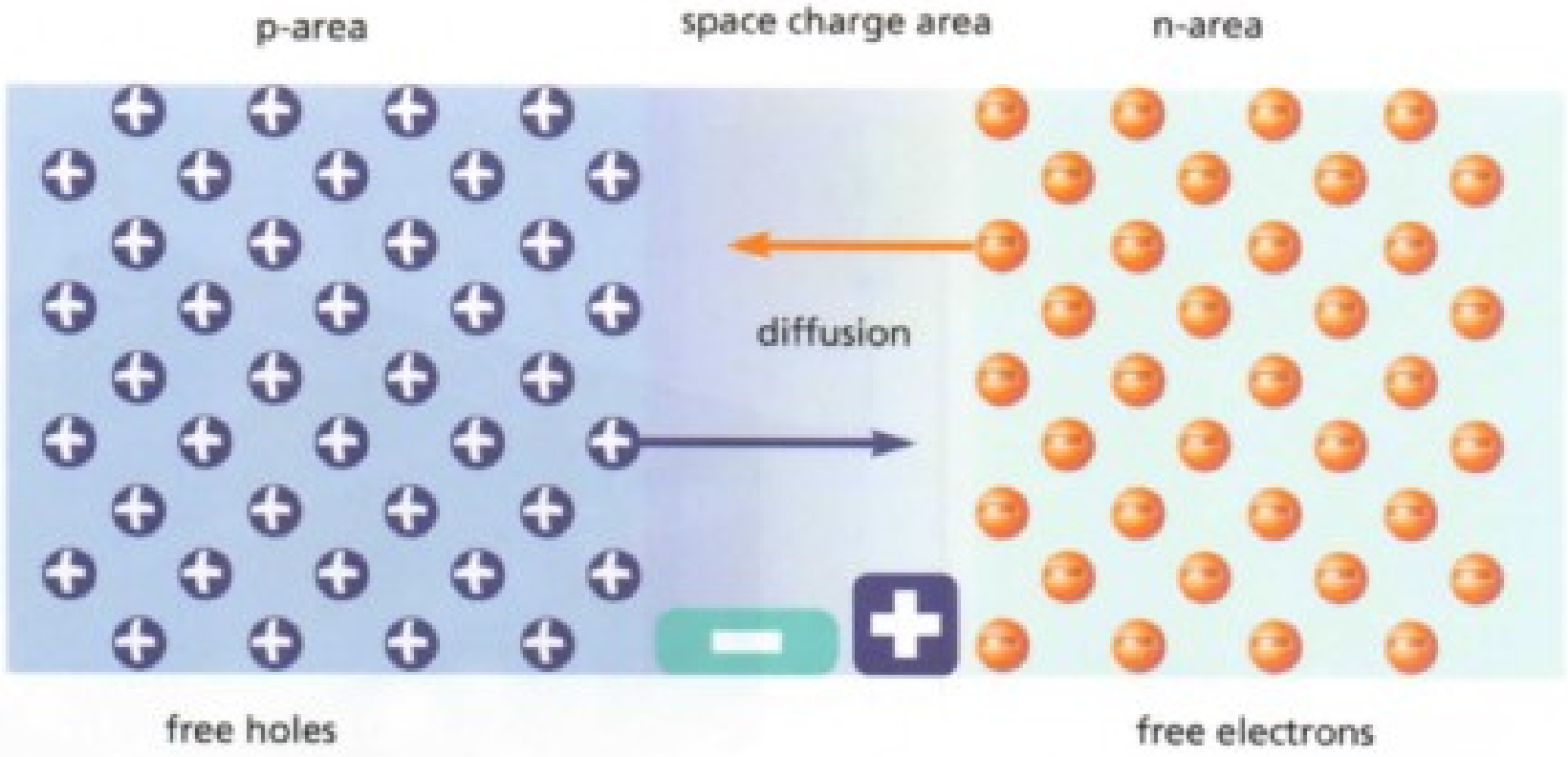
The intrinsic conductivity is not big enough for power production. Therefore, additional negative and positive charges are injected by **doping**. Replacing some silicon atoms by **phosphorous** which has 5 valence electrons, one additional electron is injected which is not involved in the bonding and can therefore freely move through the crystal. The silicon crystal is therefore called **n-doped**. In contrast, doping the crystal by **boron** which has only 3 valence electrons, one electron is missing for the bonding creating a hole which is positively charged and can also move through the crystal. The crystal is **p-doped**.



Source: V. Quaschning

How Solar Cells Work

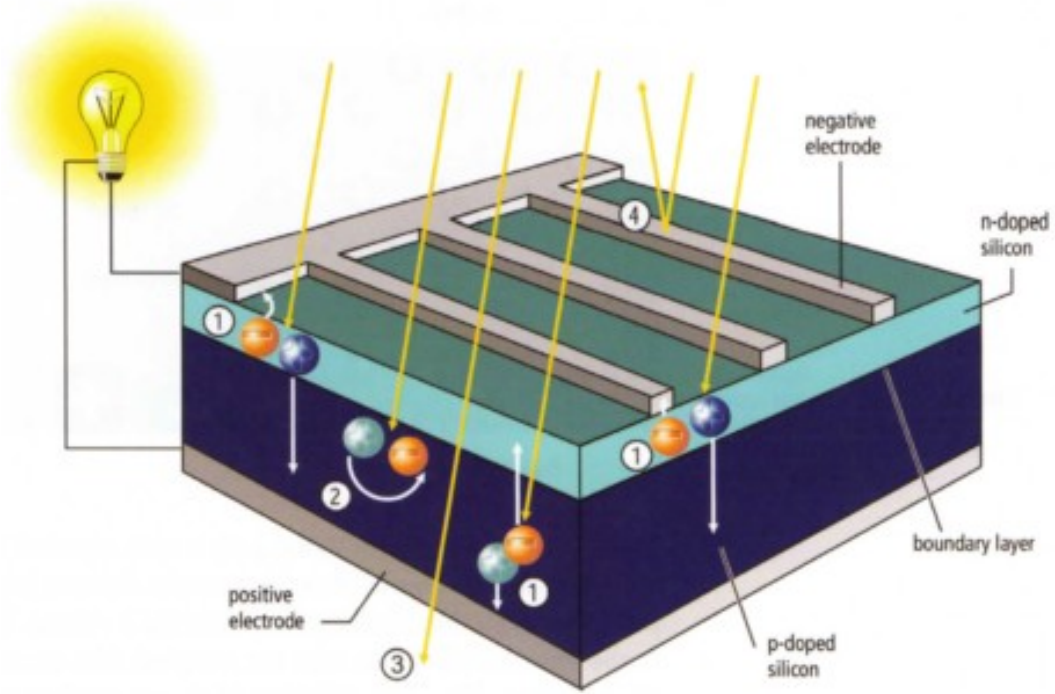
If a n-doped and p-doped silicon crystal are brought together a **p-n-junction** is formed. Diffusion of electrons and holes into the each other region sets in. As a result, the n-area becomes a bit more positive and the p-area a bit more forming an **intrinsic electric field**. This field stops the diffusion at a certain point.



Source: V. Quaschning

How Solar Cells Work

The p-n-semiconductor is a **solar cell**. If the p-n-semiconductor is exposed to light, photons are absorbed by the electrons. This input energy breaks the electron bonds and the released electrons now move towards the n-area due to the intrinsic electric field. As a result, the n-area has additional electrons and the p-area additional holes. In other words, charge separation happened causing a light induced electric field or voltage. If the solar cell is integrated into an electric circuit, electrons from the n-area (typically the surface of the cell) move through the load (e.g. a lamp) to the p-area.



1 – Charge separation in the p-n-semiconductor
2 – Recombination
3 – Unused photon energy by transmission
4 – Reflection and shading by front contacts

Source: V. Quaschning

How Solar Cells Work

The generated current in the ciruit is a direct current (DC). The efficiency of solar cells are determined by recombination processes between electrons and holes before the charge separation were happen, and transmission and reflection. Furthermore, not the whole solar spectrum is available to solar cells since the photons have to have a certain energy in order to get absorbed by the electrons. In silicon photovoltaic cells, photons with wavelength in the red and infrared tail of the solar spectrum are absorbed. In total, only 15% to 20% of the incident light is converted into electricity.

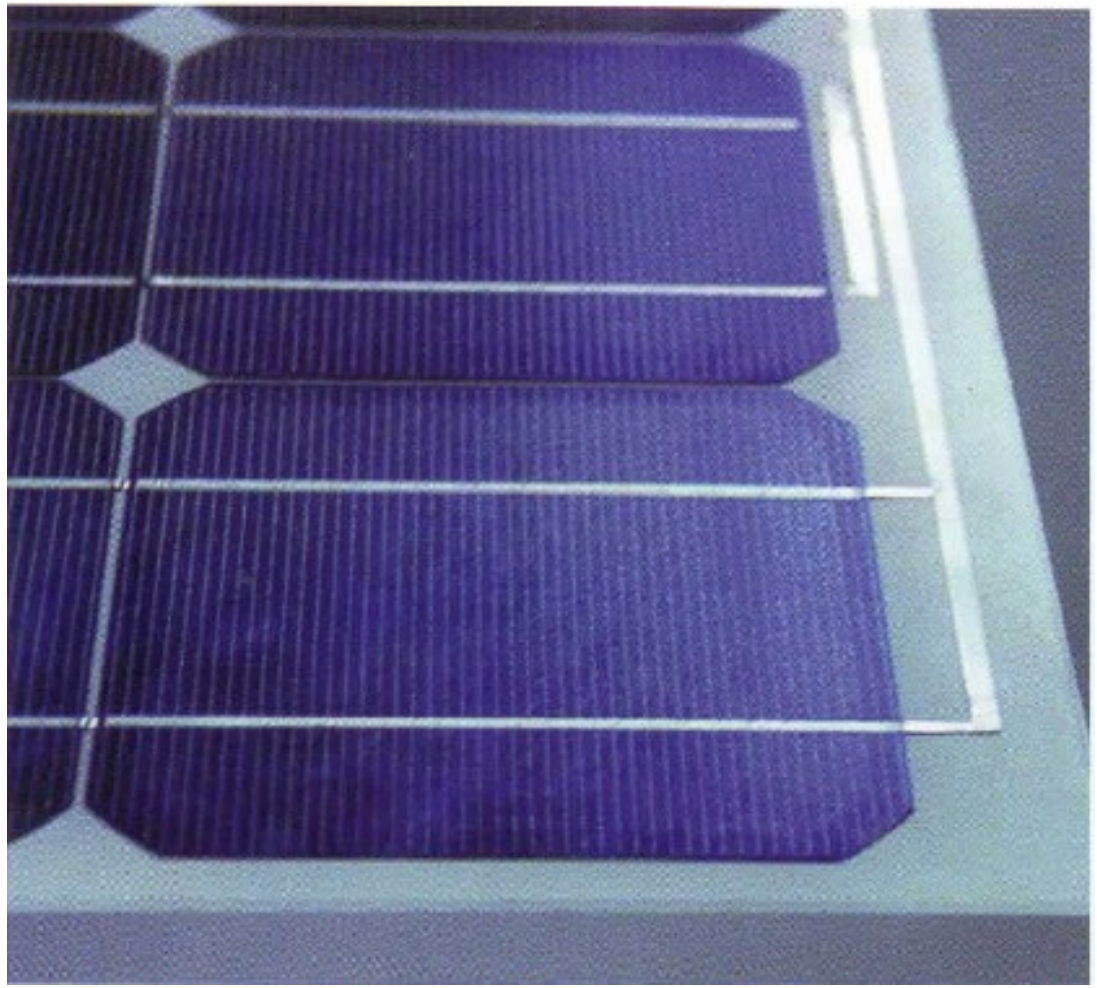
Please see the following video for detailed explanations and illustrations
https://www.youtube.com/watch?v=u0hckM8TKY0

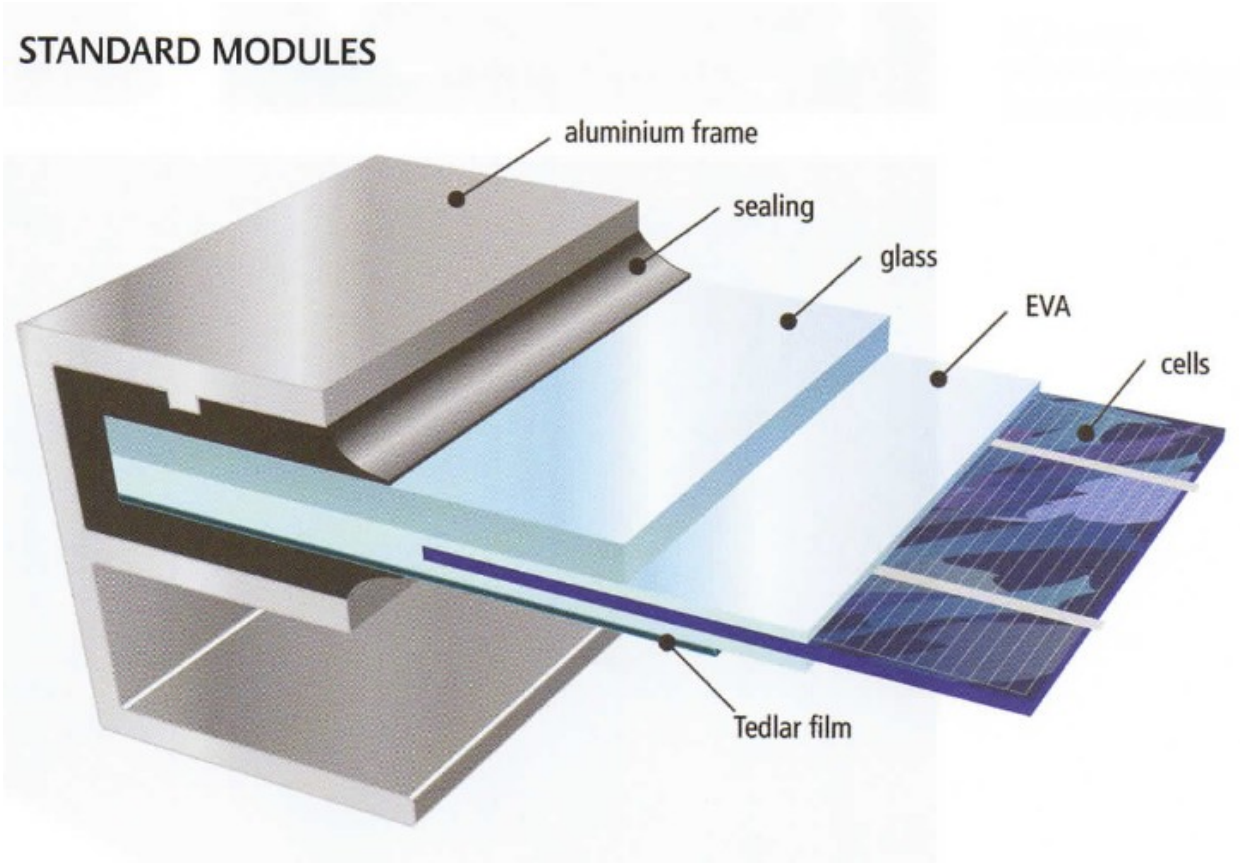
Photovoltaic Technologies

04

Photovoltaic Technologies

Photovoltaic Cells and PV module

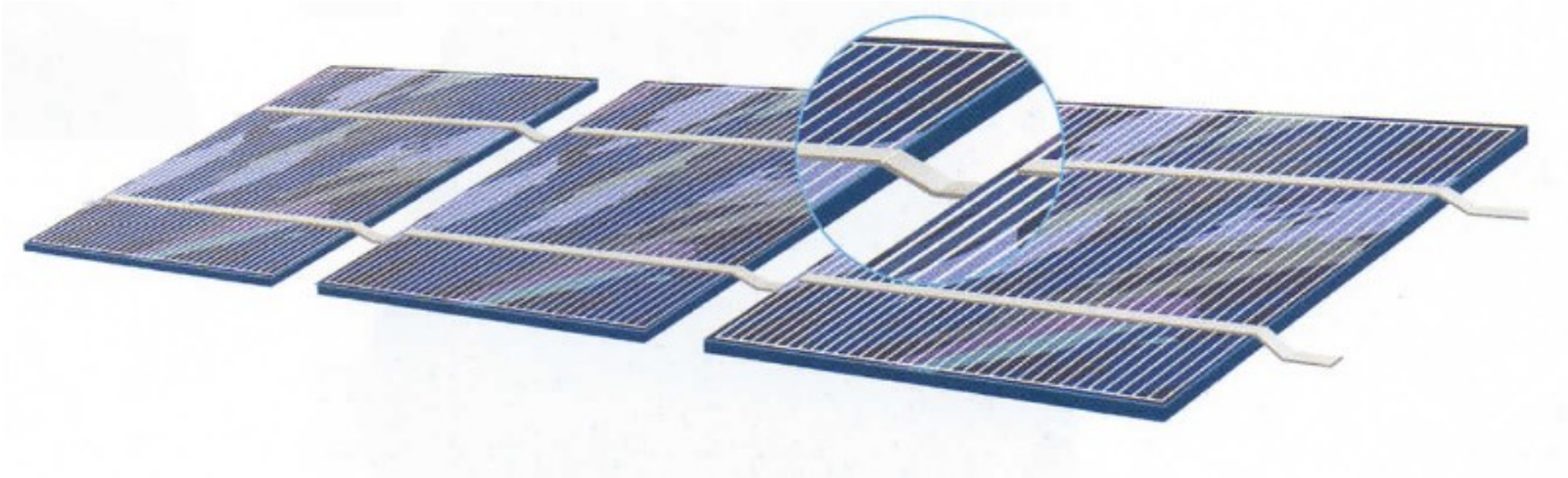




Frame of a standard module
Source: Pilkington Solar

Photovoltaic Technologies

Serial connection of cells in a PV module



Photovoltaic Technologies

Standard monocrystalline Silicon cells (1st generation PV technology)

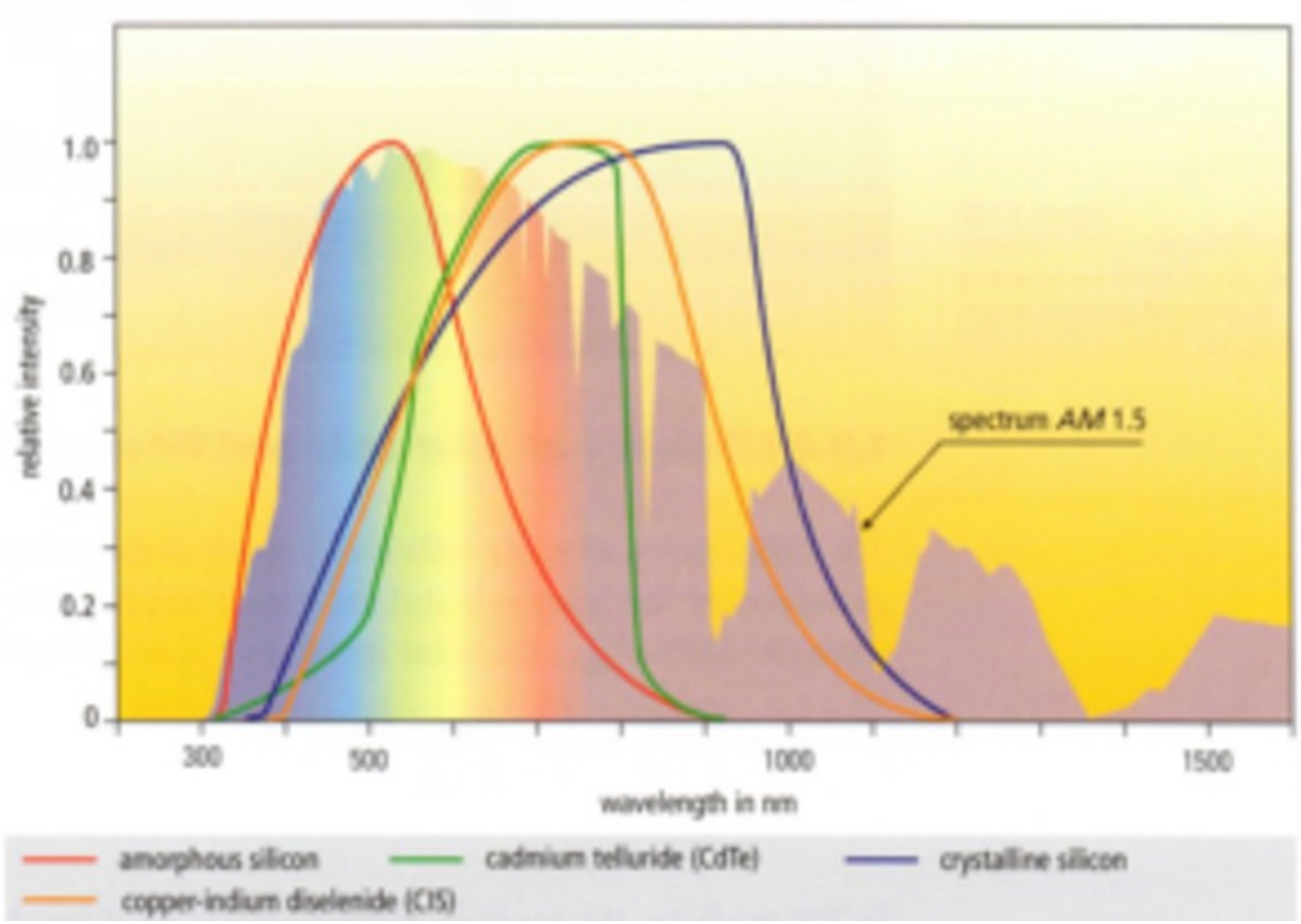
- Fabrication requires high temperatures (up to 2000°C)
- Absorption in the red
- Efficiency 18-20%
- Usual Sizes 10cm² x 10cm²,
- Thickness 0.2 mm to 0.3 mm
- Colour: dark blue to black

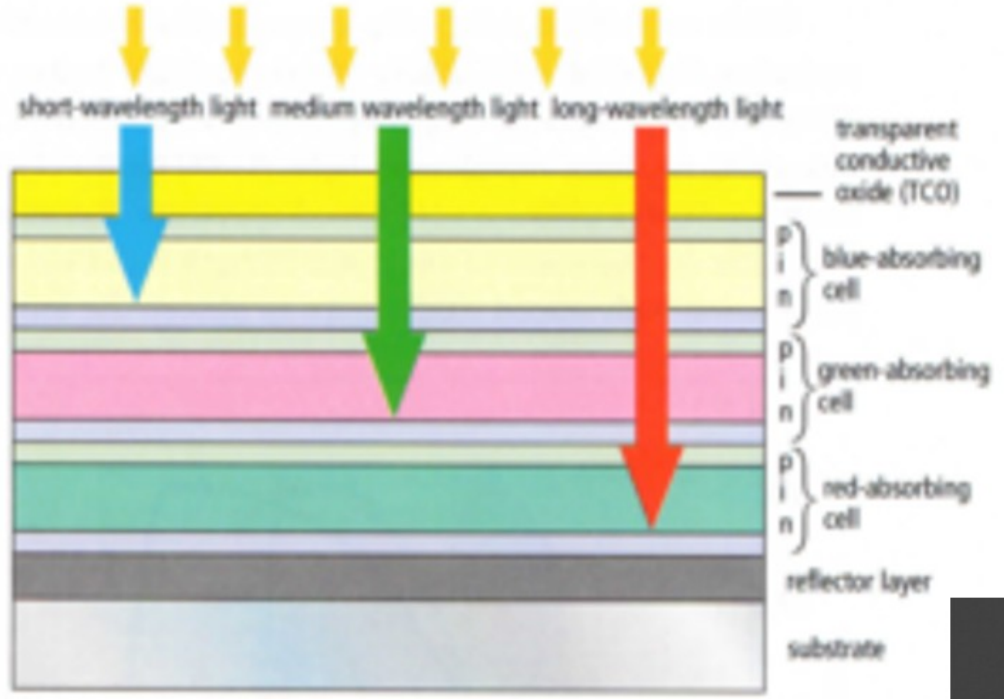
Thin film technology (2nd generation PV technology)

- Amorphous silicon cells, only low temp up to 250 °C, efficiency about 7%, absorbtion in the blue
- Copper-Indium-Diselenide cells (CIS), temp about 600 °C, efficiency about 11%, absorbtion in the gree-yellow
- Cadmium-Telluride cells (CdTe), about to 600 °C, efficiency about 8%, absorbtion in the green-yellow

Photovoltaic Technologies

Triple junction cells





Photovoltaic Technologies

Newest Thin film technology

- III-V semiconductors such as Gallium-Arsenide (GaAs), Germanium (Ge), Perovskite, efficiencies 30% and more are possible

Organic Cells and Grätzel Cells (3rd generation PV technology)

- Flexible, easy to manufacture at low temp
- Different operation principle: no p-n junction but light absorbing dye molecules like Titanium dioxide (TiO_2)
- Long-term chemical stability still a problem
- Building integrated PV is possible with a huge potential

Electrical Properties of Solar Cells

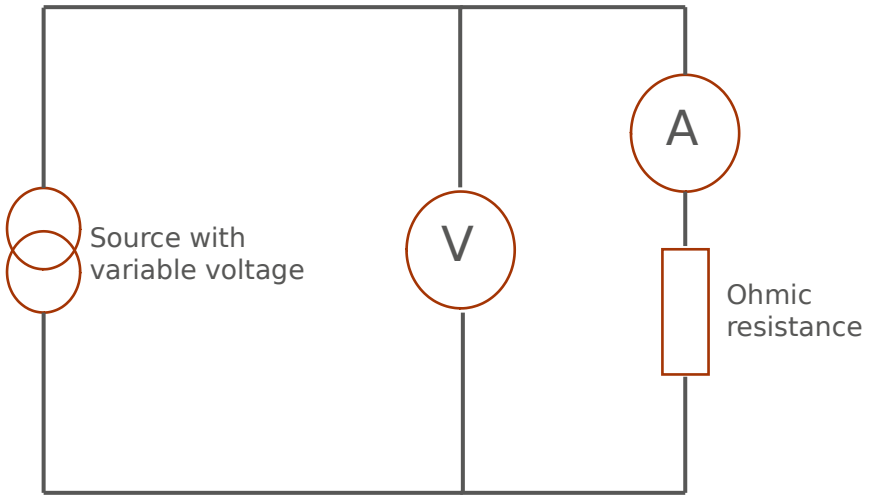
05

Electrical properties of PV cells and modules

Electric Circuits

A simple electric circuit consists of a power source like a battery, a generator etc., and different loads. Current *I* and Voltage *V* are characteristic quantities and depend on each other corresponding to the properties of the source and loads. Therefore, I-V-curves are measured and determined for the different loads in the circuit.

Example 1: Variable source and an ohmic resistance



While increasing the voltage of the source the corresponding current ***I*** (in A) and voltage ***V*** (in V) at the ohmic resistance are measured in order to determine the characteristic I-V-curve of the resistance

Electrical properties of PV cells and modules

Electric Circuits

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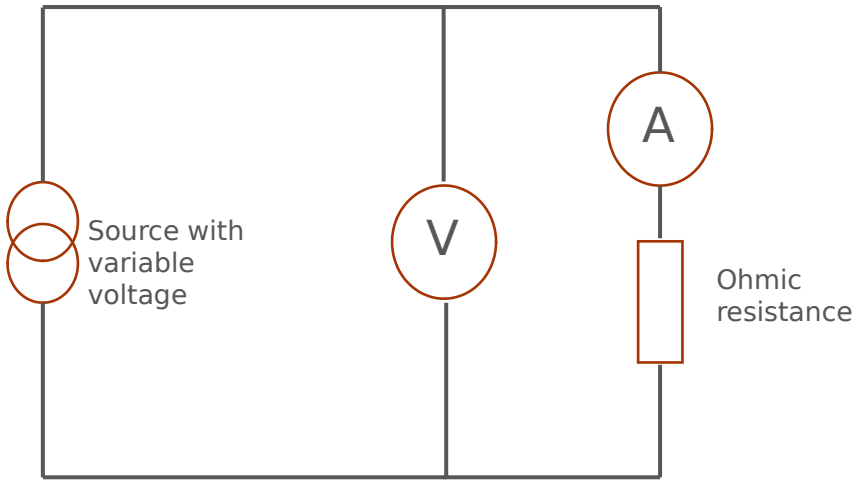

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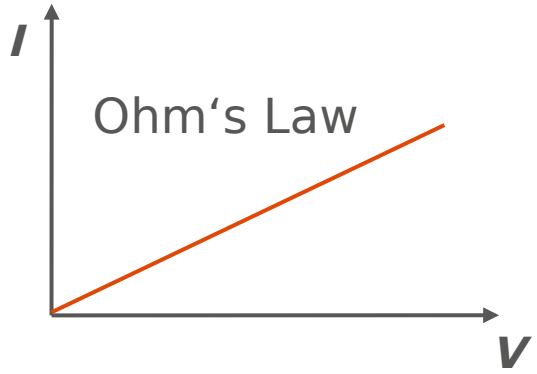
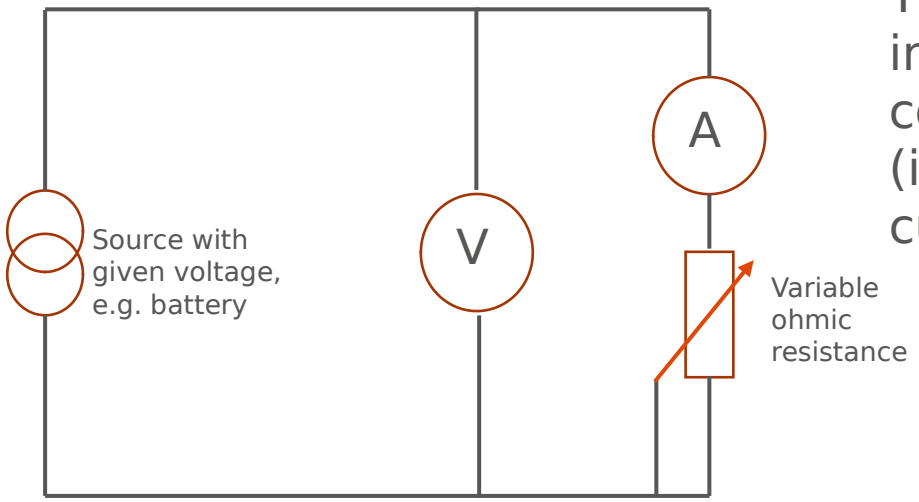


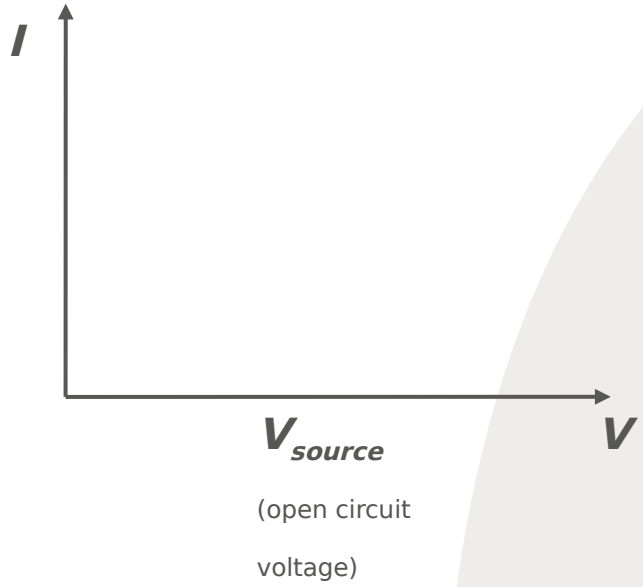
Electrical properties of PV cells and modules

Electric Circuits

Example 2: Given source and a variable ohmic resistance



The source delivers a given voltage. While increasing the ohmic resistance the corresponding current ***I*** (in A) and voltage ***V*** (in V) are measured to determine the I-V-curve



Electrical properties of PV cells and modules

Electric Circuits

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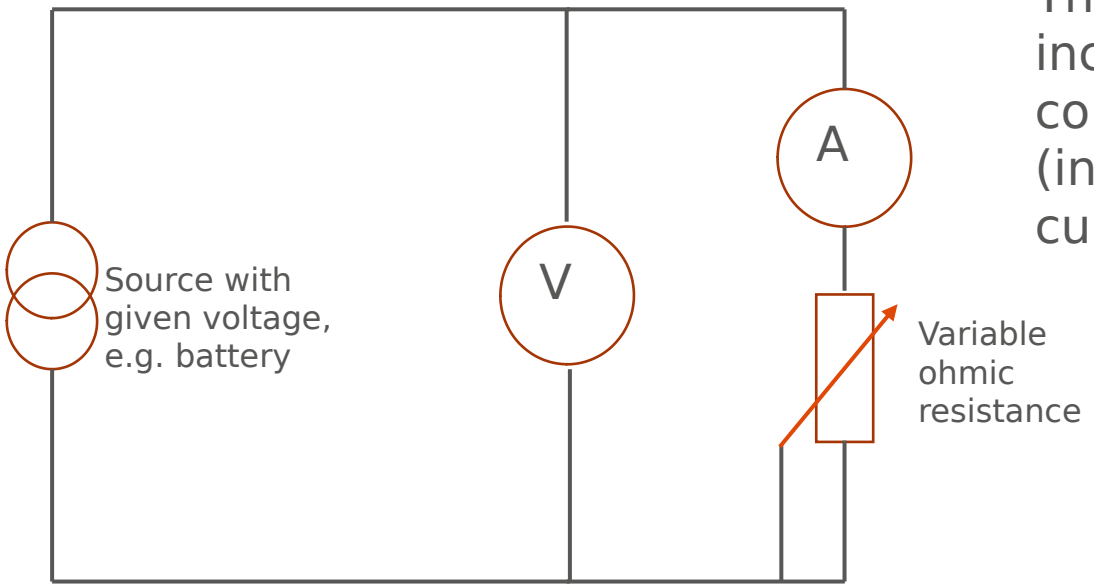

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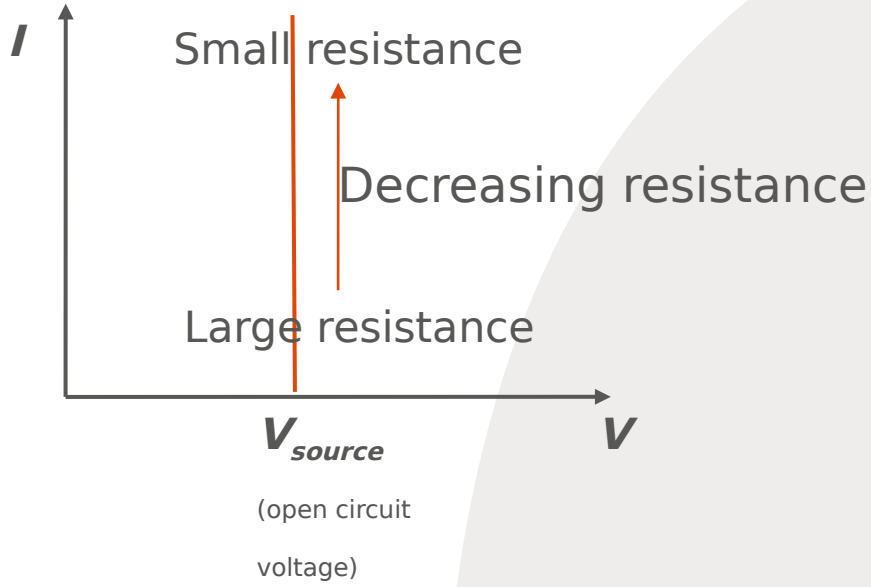
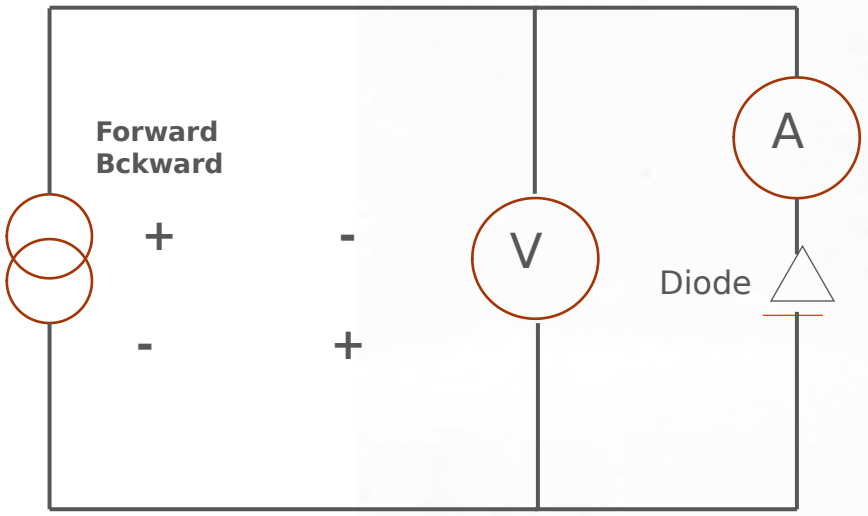


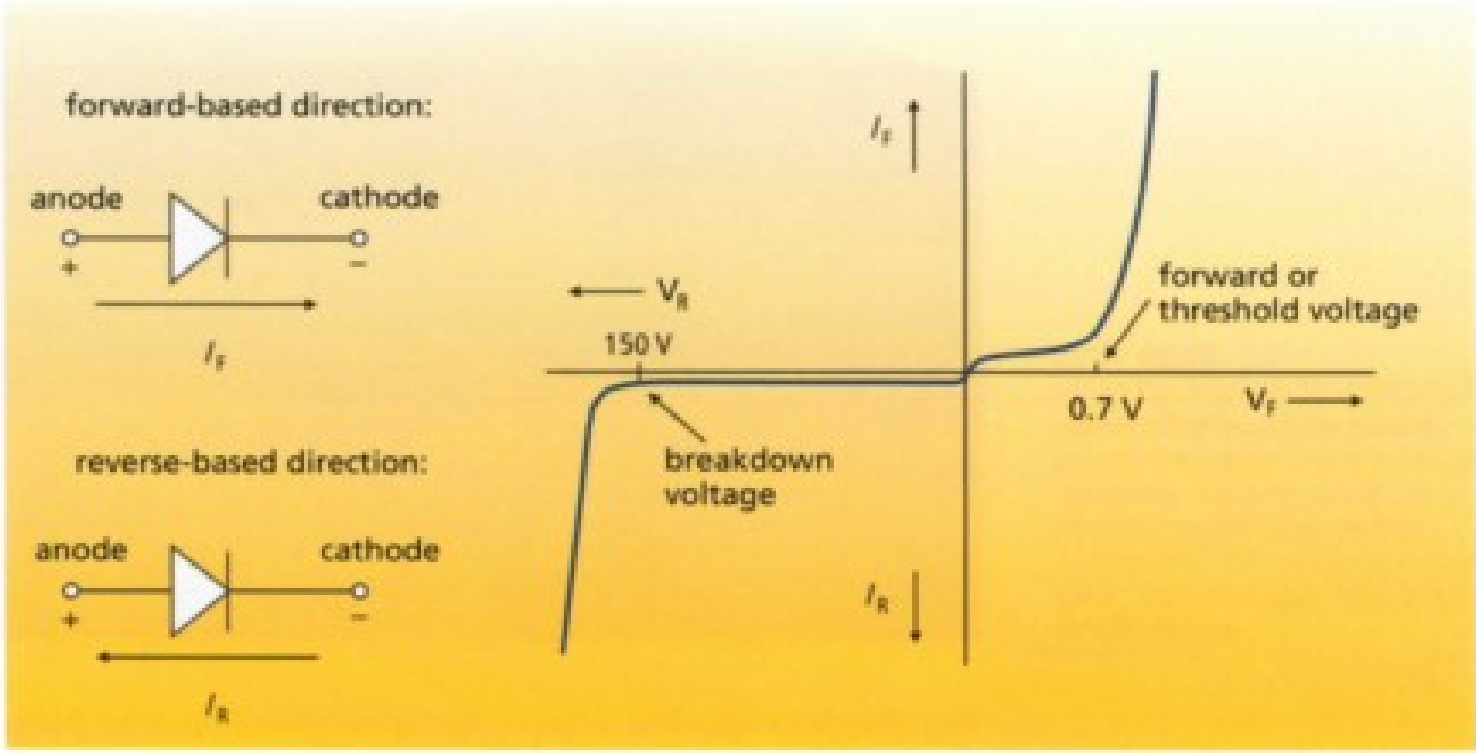
Electrical properties of PV cells and modules

Electric Circuits

Example 3: I-V-curve of a diode



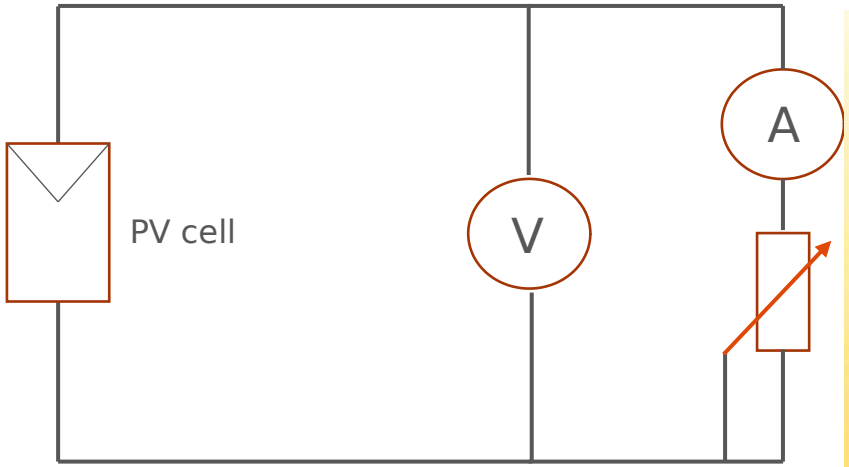
Current voltage curve for silicon diode BAY 45
Source: R. Haselhuhn

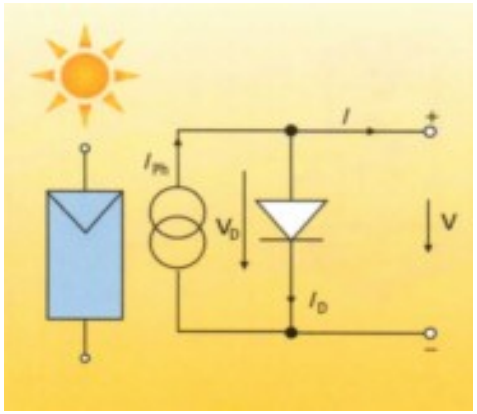


Electrical properties of PV cells and modules

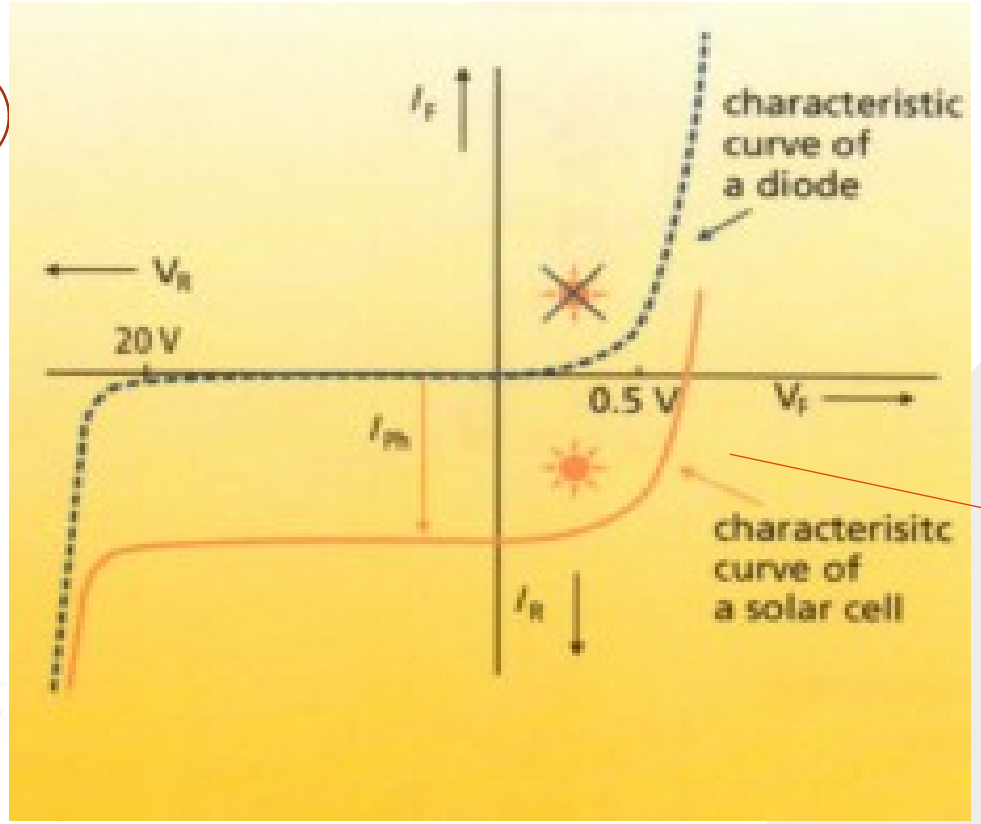
Electric Circuits

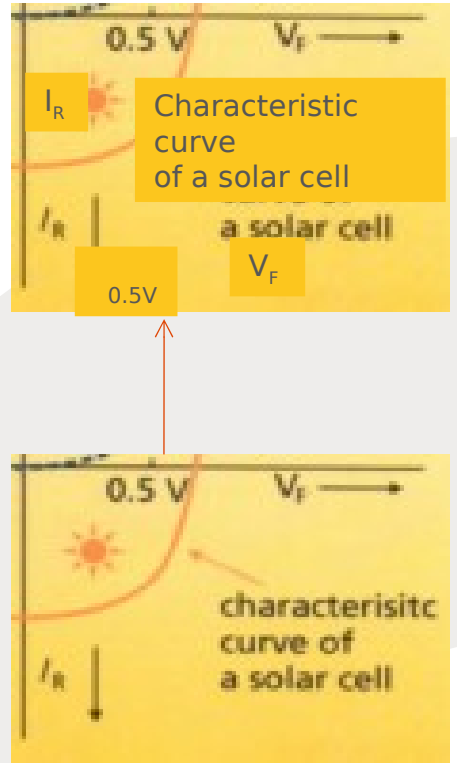
Example 4: I-V-curve of a dark and illuminated photovoltaic cell





Illuminated equivalent circuit diagram and characteristic curve
Source: R. Haselhuhn

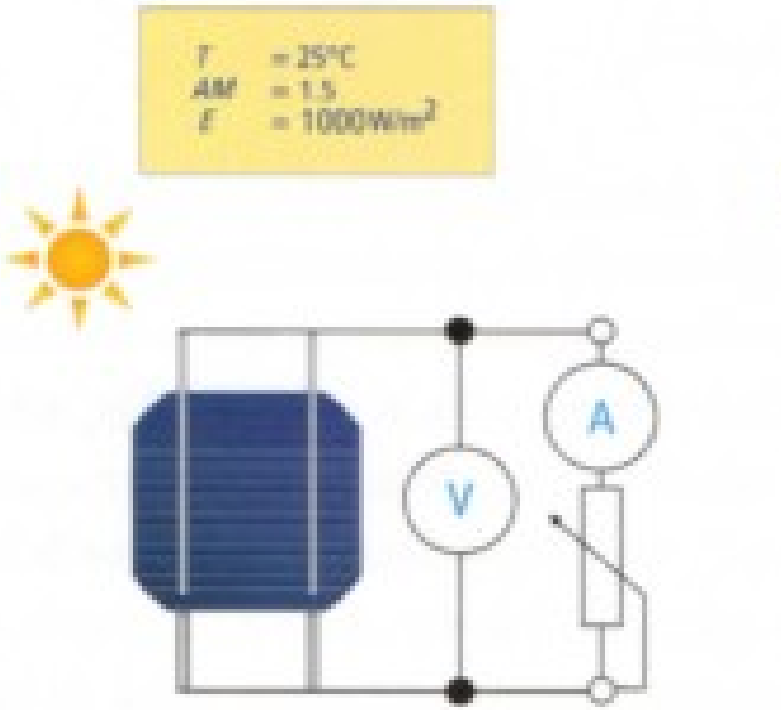


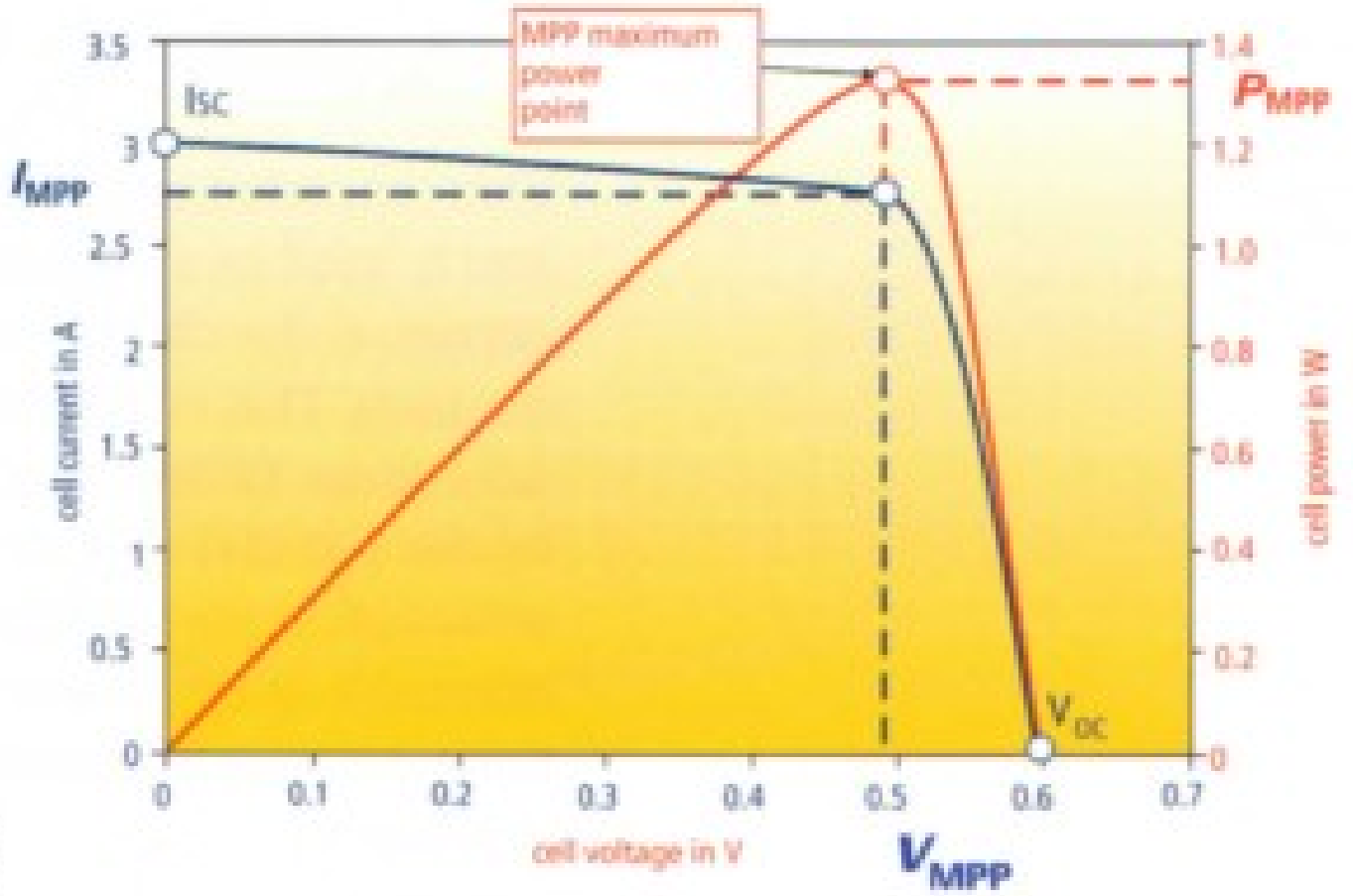


Electrical properties of PV cells and modules

Electric Circuits

Example 5: I-V-curve of an illuminated photovoltaic cell and Maximum Power

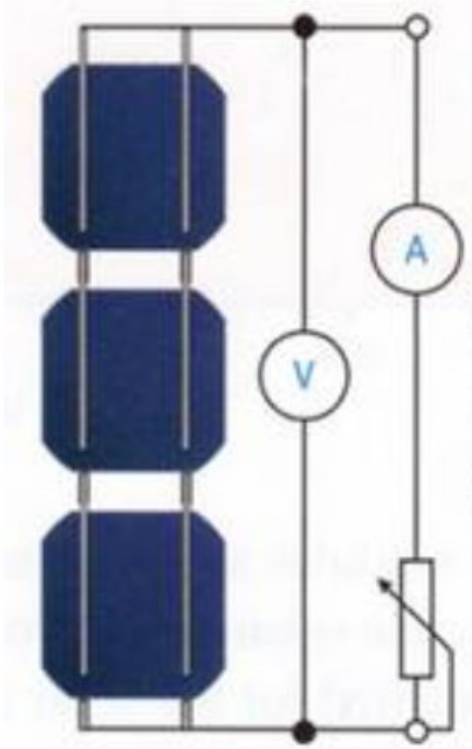




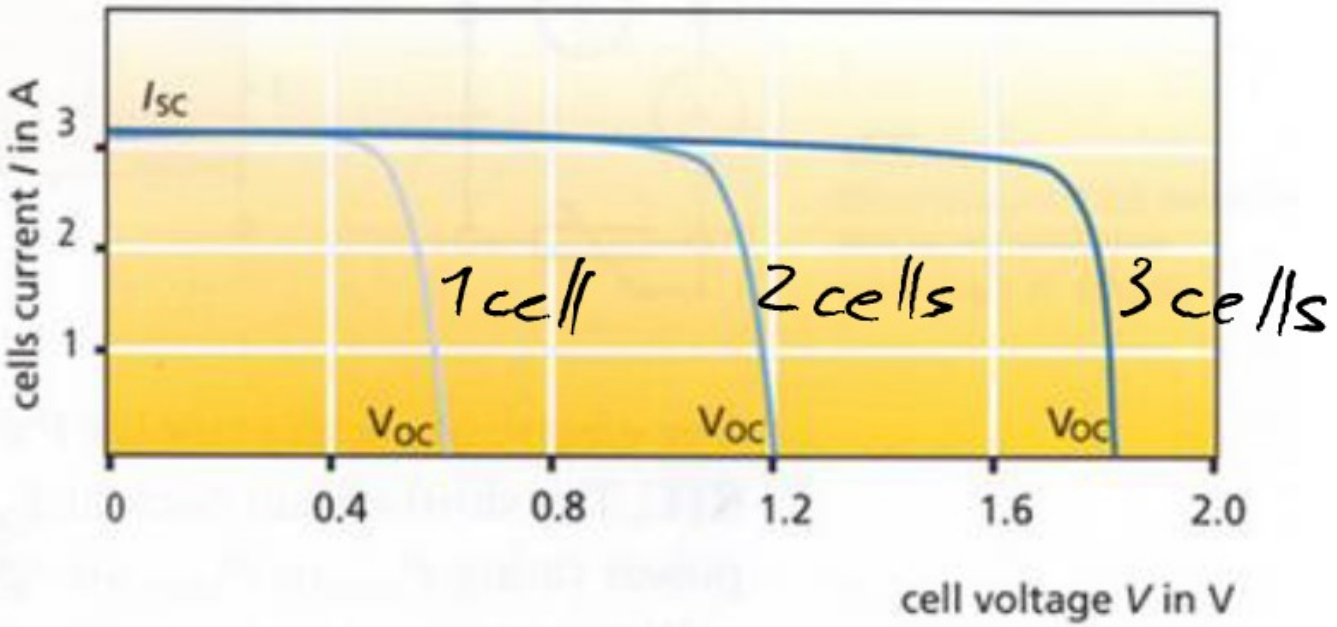
Current/voltage characteristic curve (I–V curve) for a crystalline silicon solar cell
Source: R. Haselhuhn

Electrical properties of PV cells and modules

Serial connection of cells

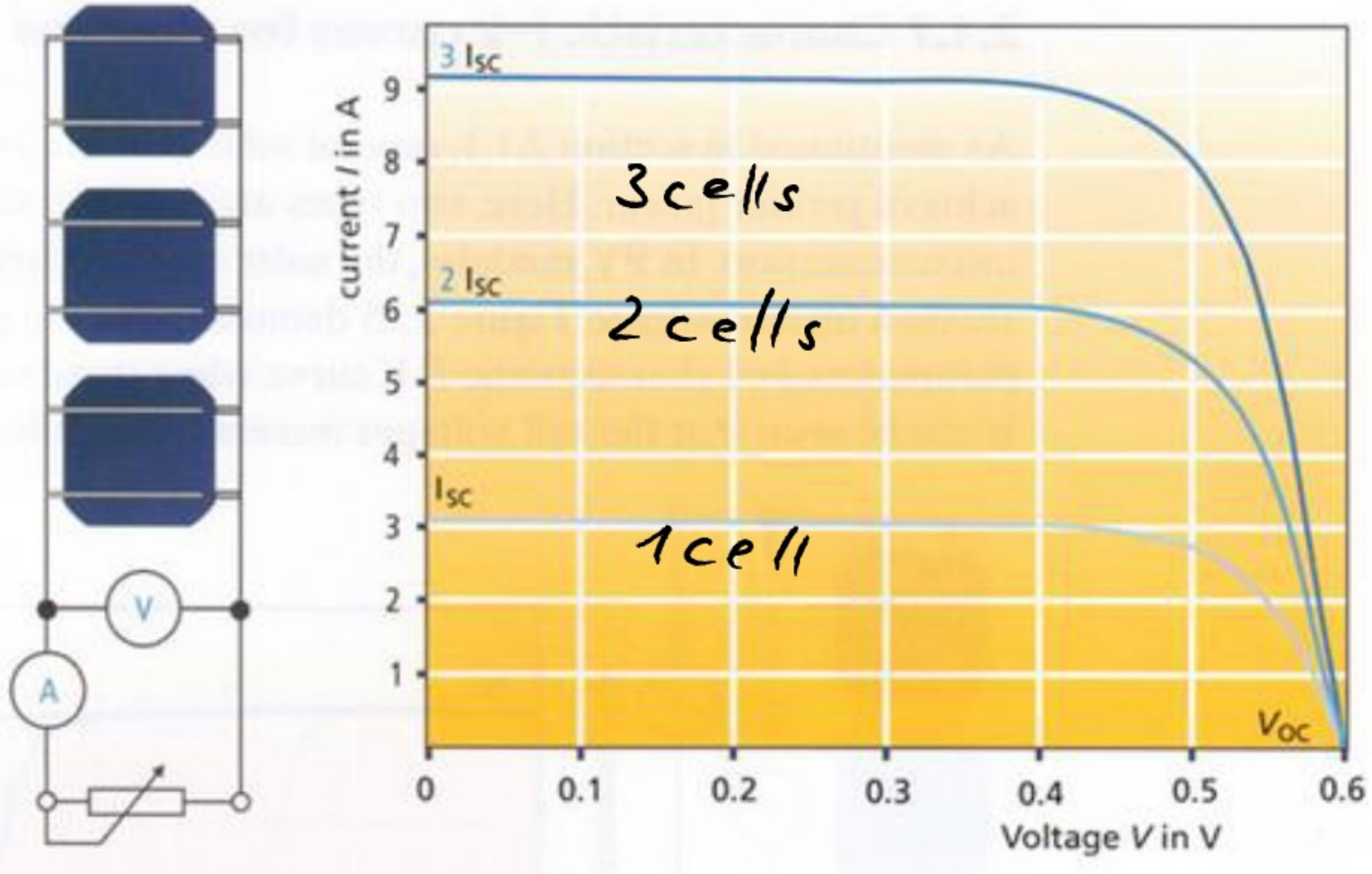


If cells are connected in series, the open circuit voltage is doubled, tripled, etc. whereas the short circuit current remains the same



Electrical properties of PV cells and modules

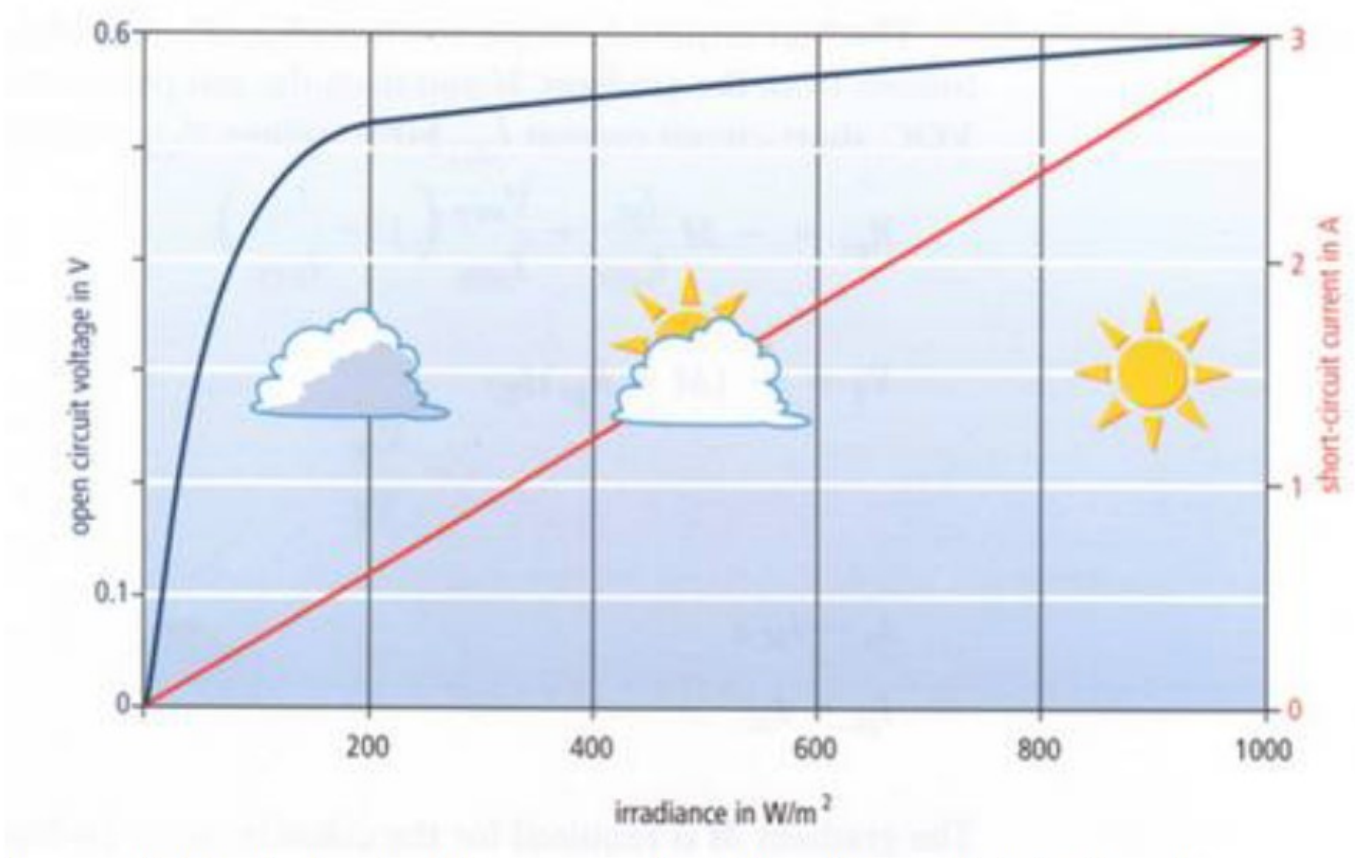
Parallel connection of cells



Here, the current is doubled, tripled, etc. whereas the open circuit voltage remains The same.

Electrical properties of PV cells and modules

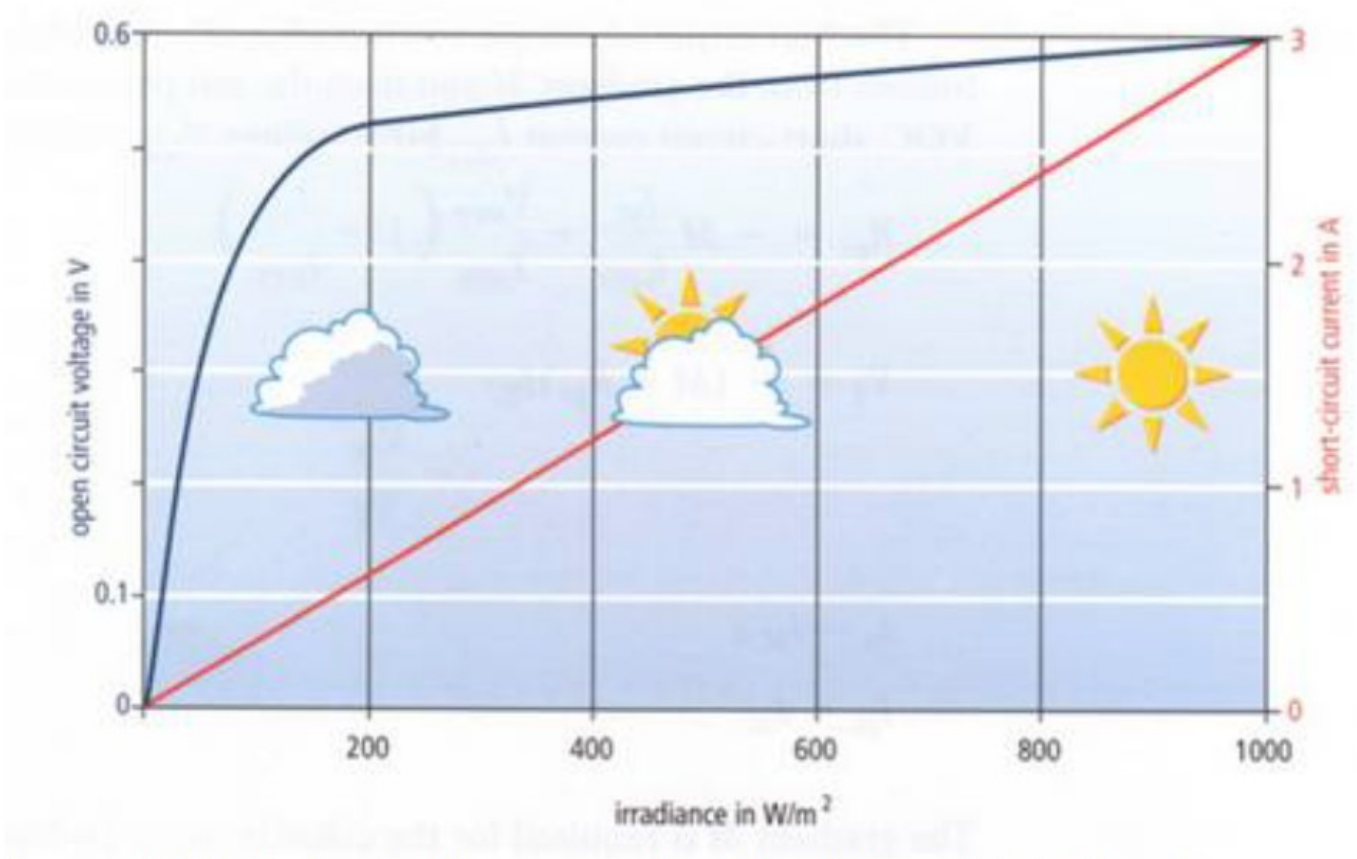
Dependency of Voc and Isc on solar light intensity



Source: R. Haselhuhn, in "Planning and Installing Photovoltaic Systems"

Electrical properties of PV cells and modules

Dependency of Voc and Isc on solar light intensity

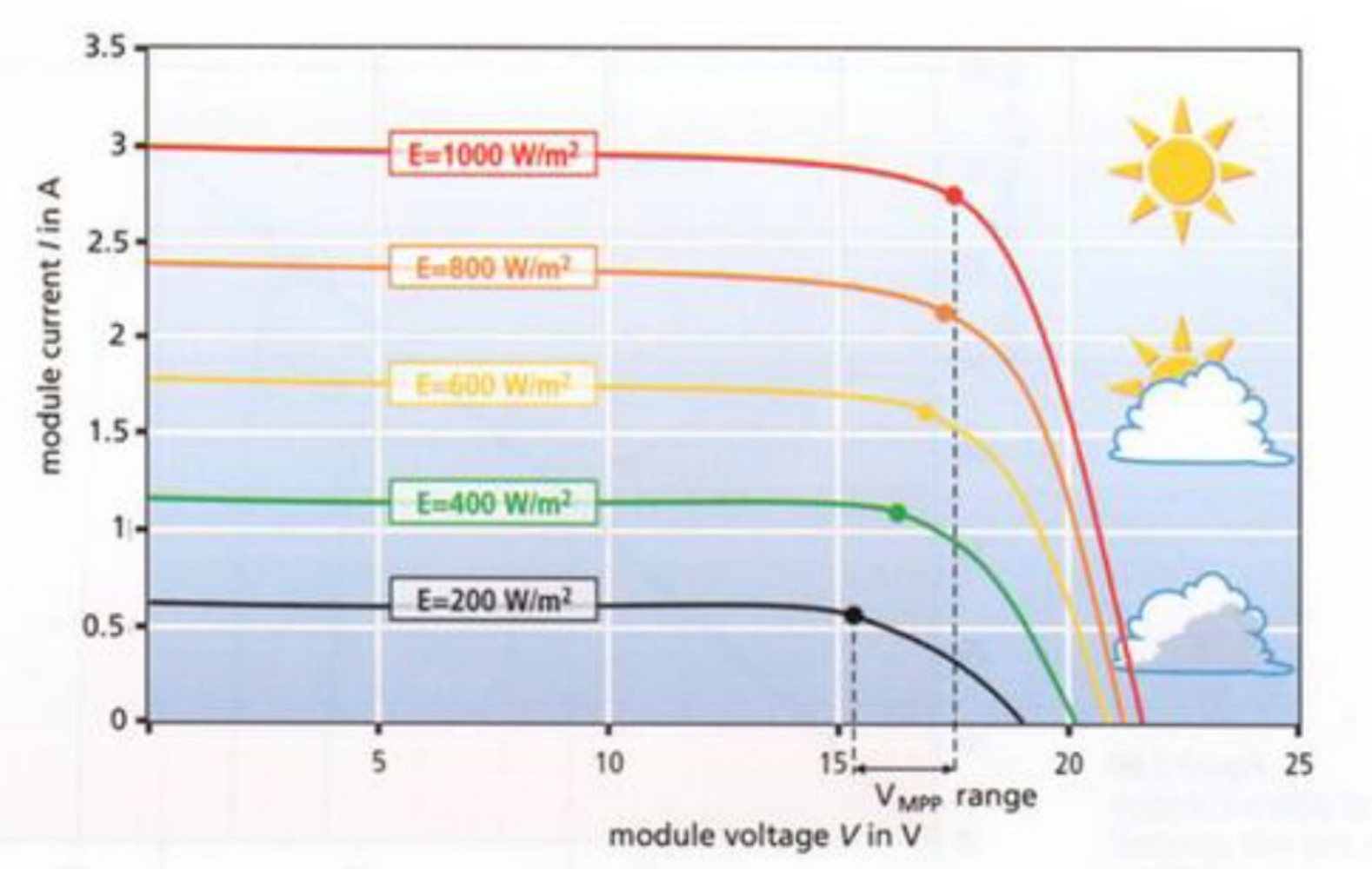


Source: R. Haselhuhn, in "Planning and Installing Photovoltaic Systems"

The open circuit voltage Voc shows a steep rise at low light intensities and stays relatively constant for medium and higher light intensities. In contrast, the short circuit current Isc rises linearly with the light intensity.

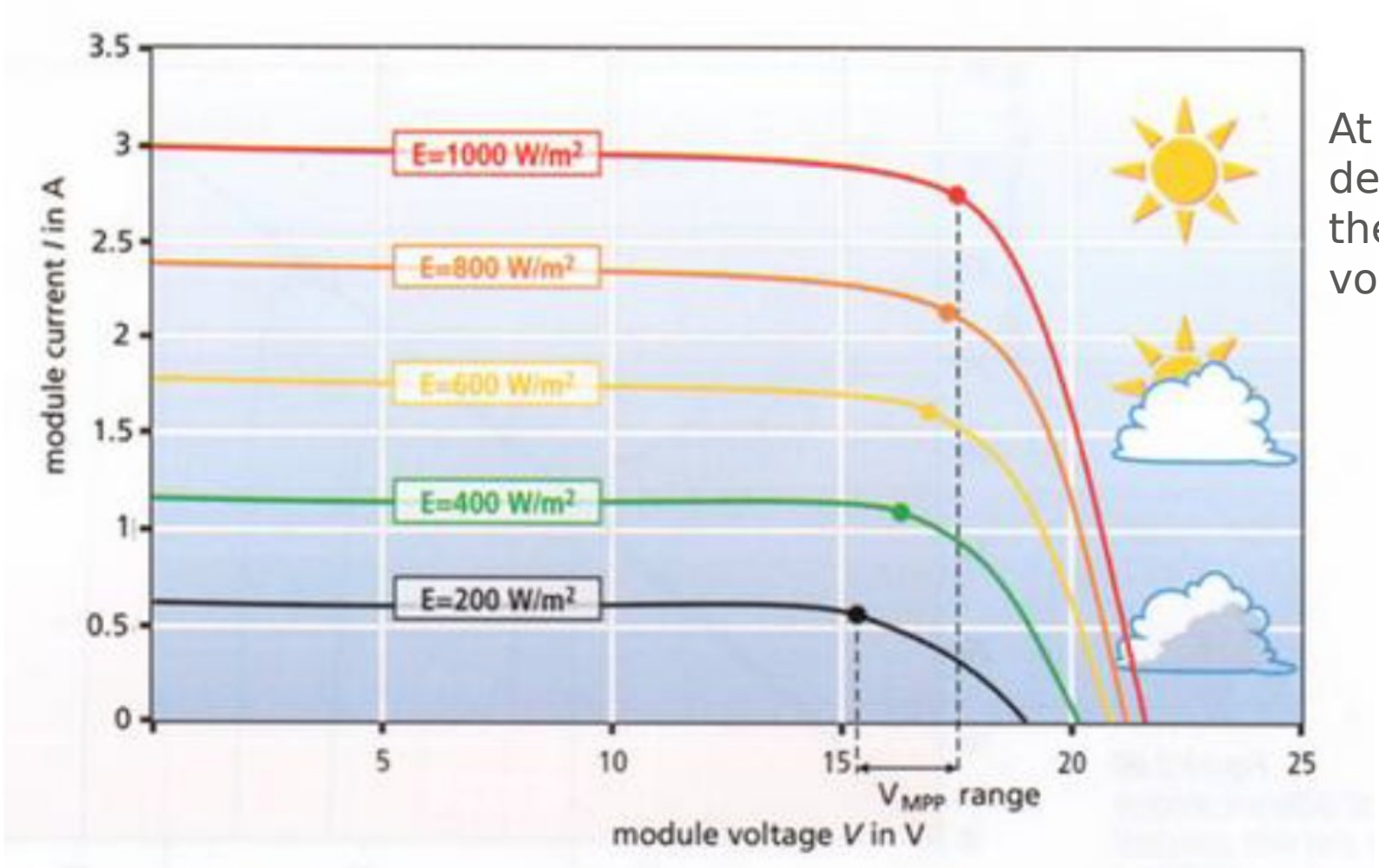
Electrical properties of PV cells and modules

Dependency of the I-V curve on solar light intensity



Electrical properties of PV cells and modules

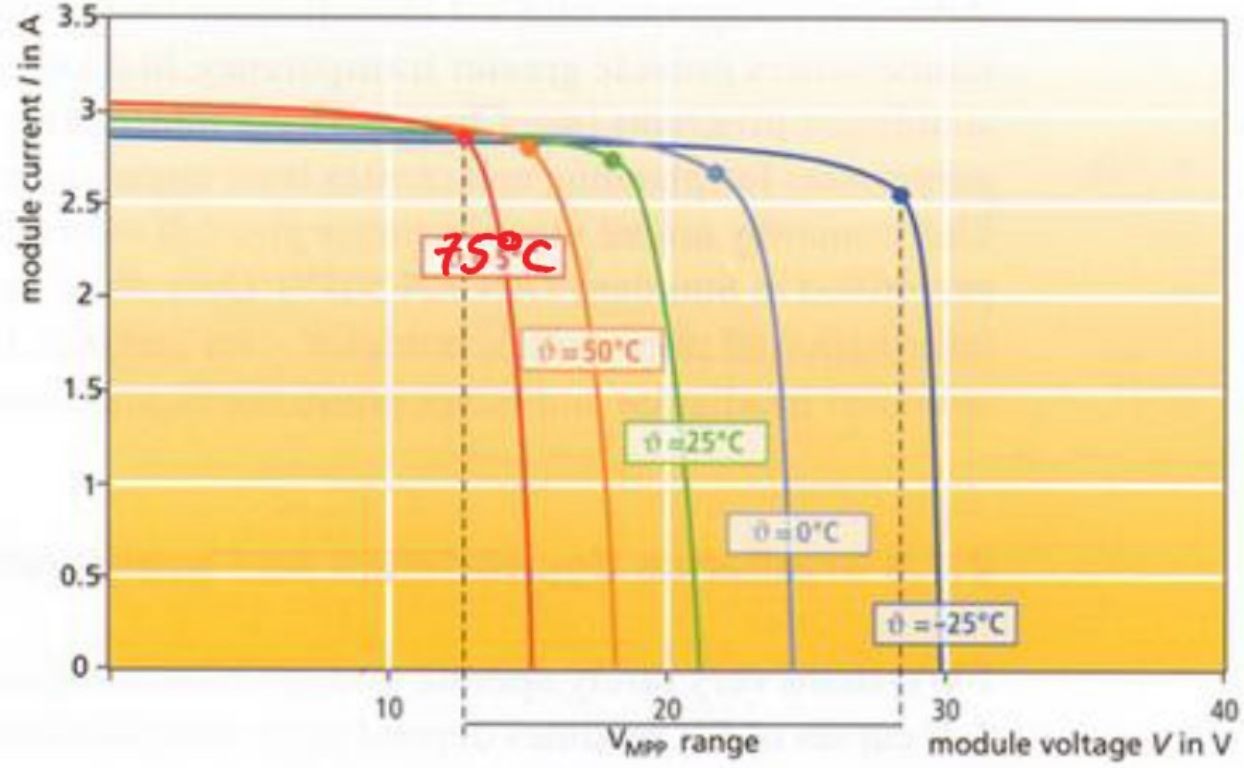
Dependency of the I-V curve on solar light intensity

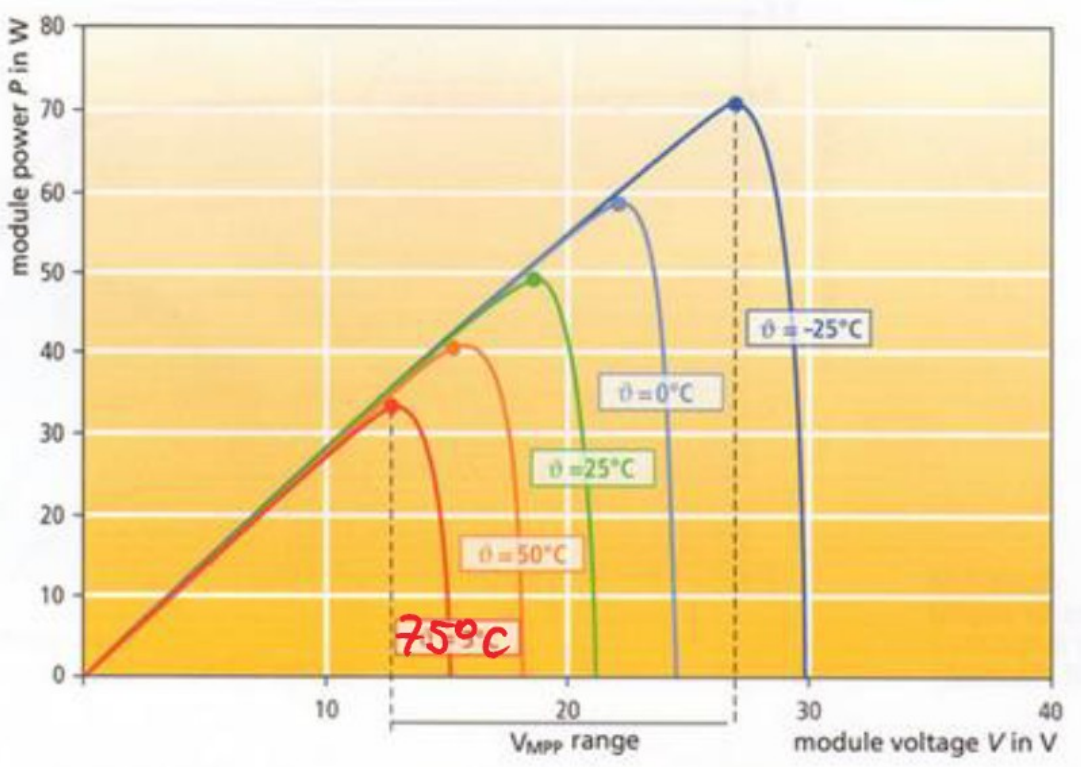


At lower light intensity the MPP decreases due to a strong drop of the current by about 80%. Also the voltage decreases but only by 20%

Electrical properties of PV cells and modules

Dependency of the I-V curve and MPP on the module temperature

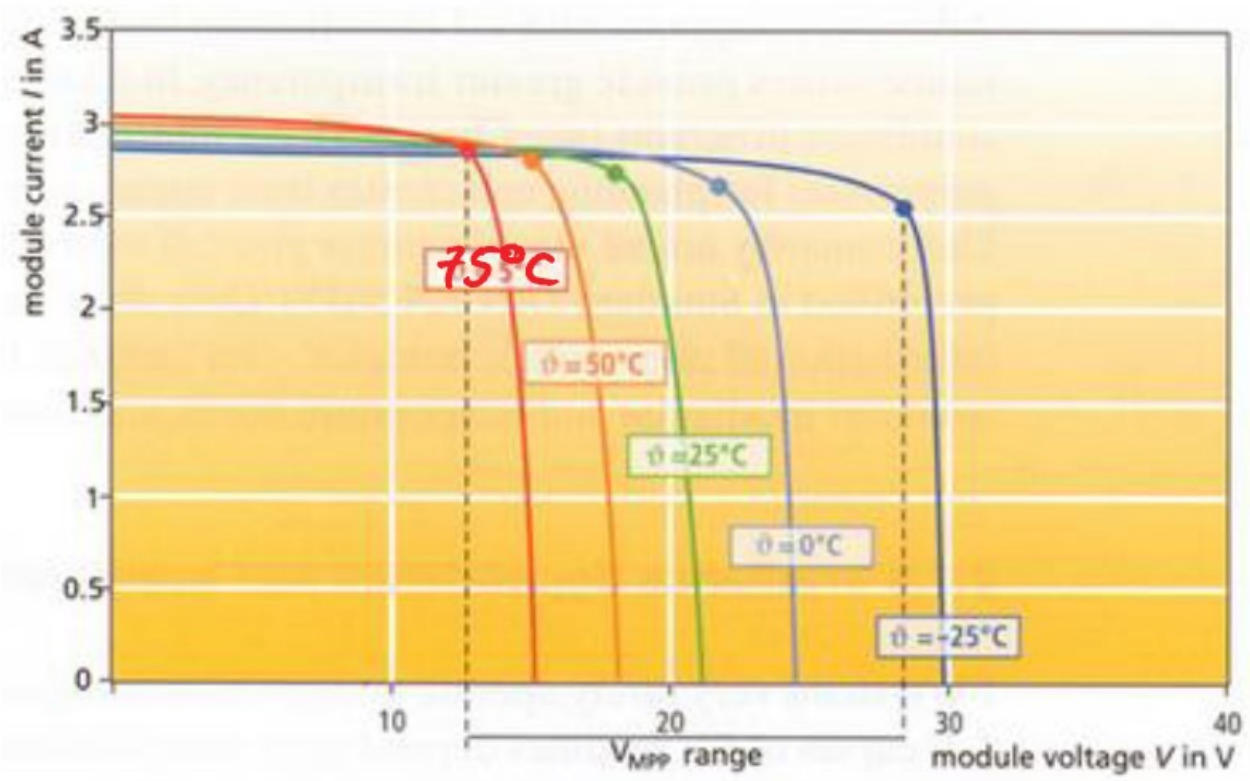


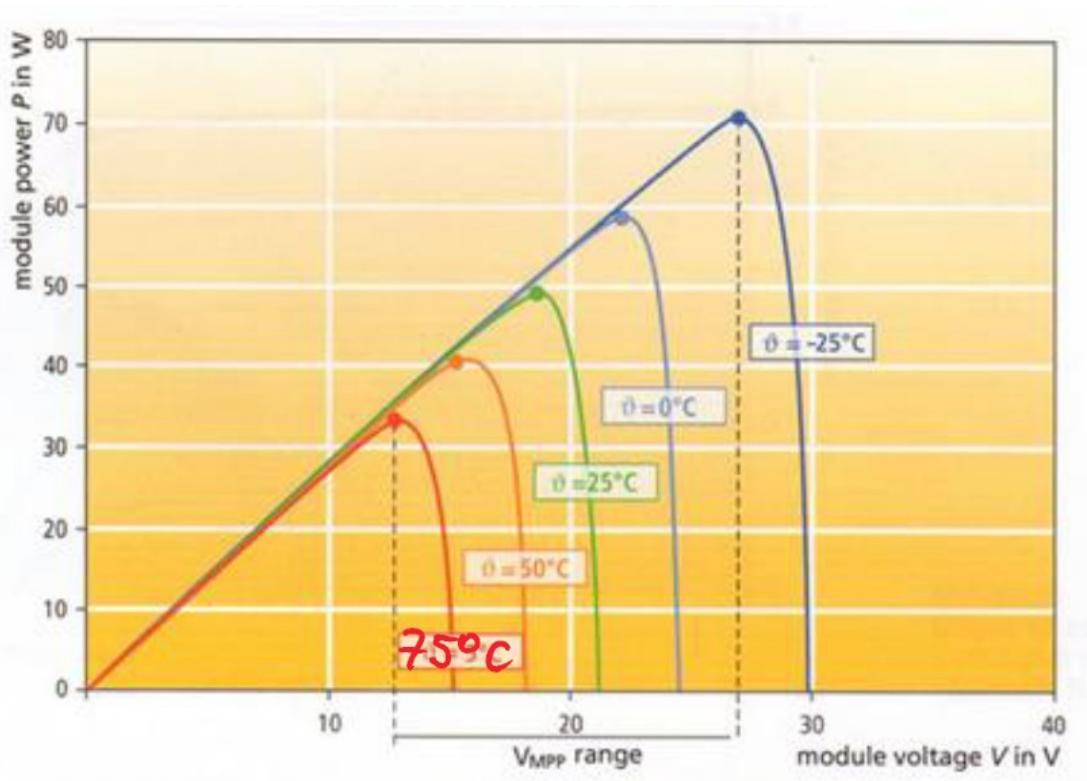


Electrical properties of PV cells and modules

Dependency of the I-V curve and MPP on the module temperature

With increasing module temperature the MPP decreases strongly due to a strong drop of the voltage. The current is not strongly influenced by temperature.





Electrical properties of PV cells and modules

Standard Test Conditions (STC)

To uniquely define MPP, voltage and current of solar cells and modules which allow to compare different ambient conditions, so called standard test conditions (STC) for the measurement of the efficiency are applied according to IEC 60904/DIN EN 60904 as follows:

1) Perpendicular irradiance of 1000 W/m^2
2) Cell temperature of 25°C with a tolerance of +/- 2°C
3) Defined light spectrum (spectral distribution of the solar reference irradiance according to IEC 60904-3) with an air mass AM=1.5

Filling Factor (FF)

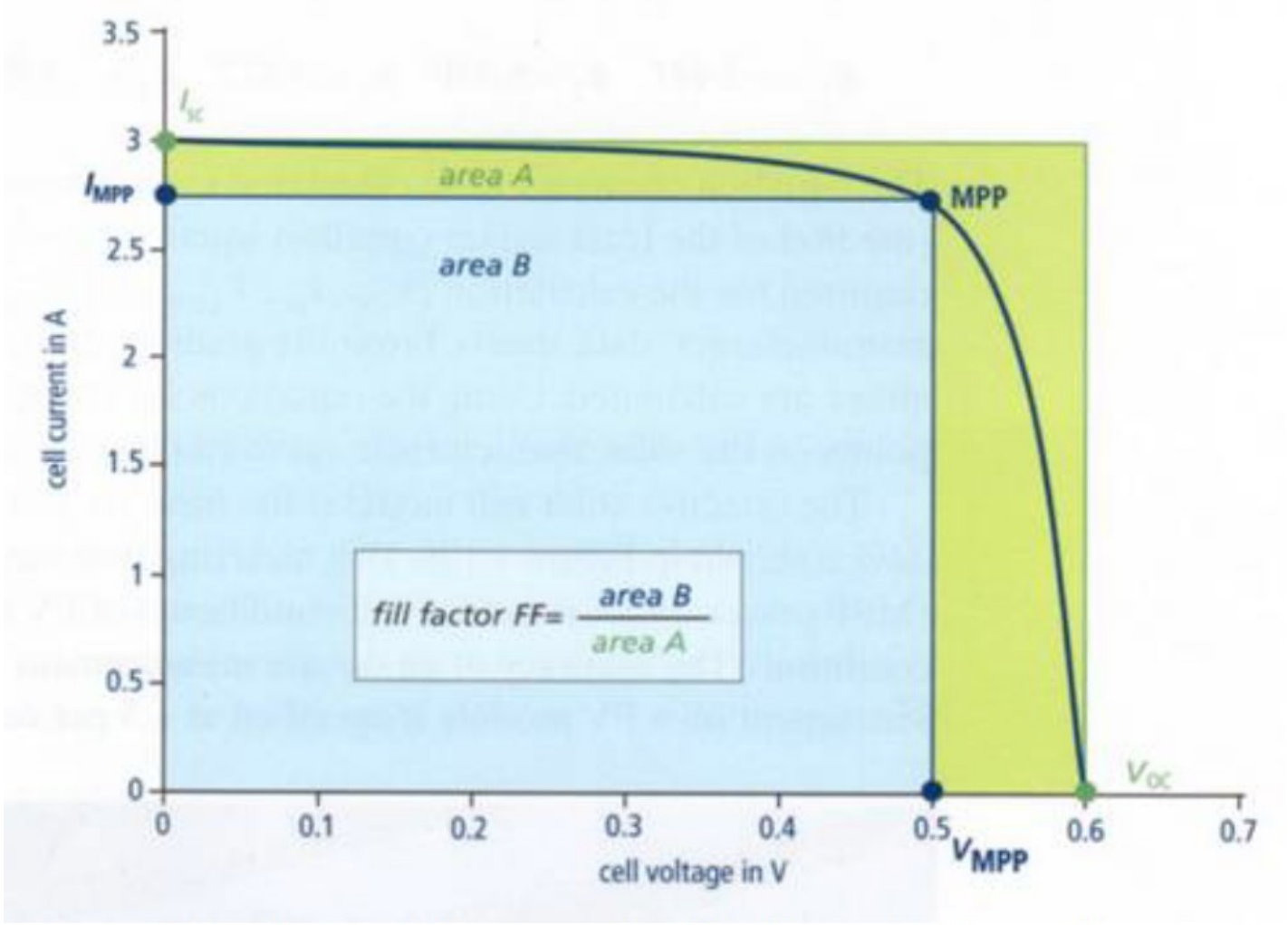
The quality of cells is often described by the so called filling factor FF defined as the quotient of MPP and the theoretical maximum power that results as the product of the short circuit current Isc and the open circuit voltage Uoc:

$$FF = P_{MPP} / U_{OC} I_{SC} = U_{MPP} I_{MPP} / U_{OC} I_{SC}$$

The higher the filling factor the better the quality of solar cells. For crystalline solar cells, the filling factor is around 0.75 to 0.85, for thin-film cells like amorphous silicon cells around 0.5 to 0.7.

Electrical properties of PV cells and modules

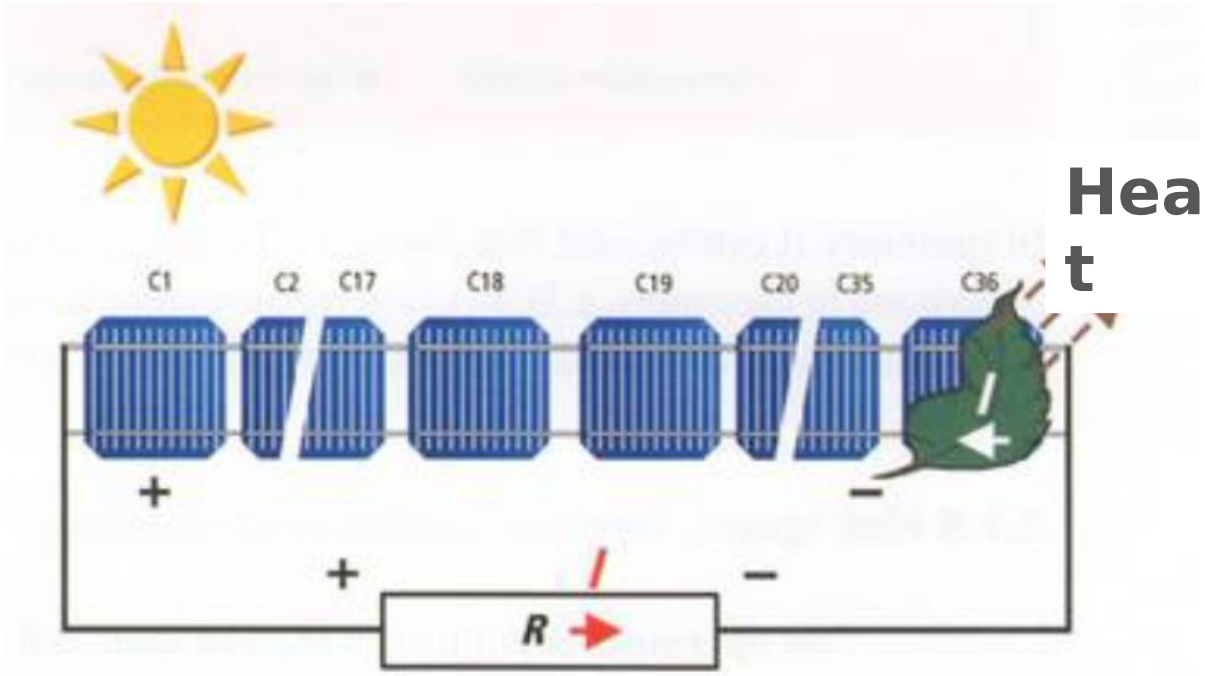
Graphical representation of the filling factor



Source: R. Haselhuhn, in "Planning and Installing Photovoltaic Systems"

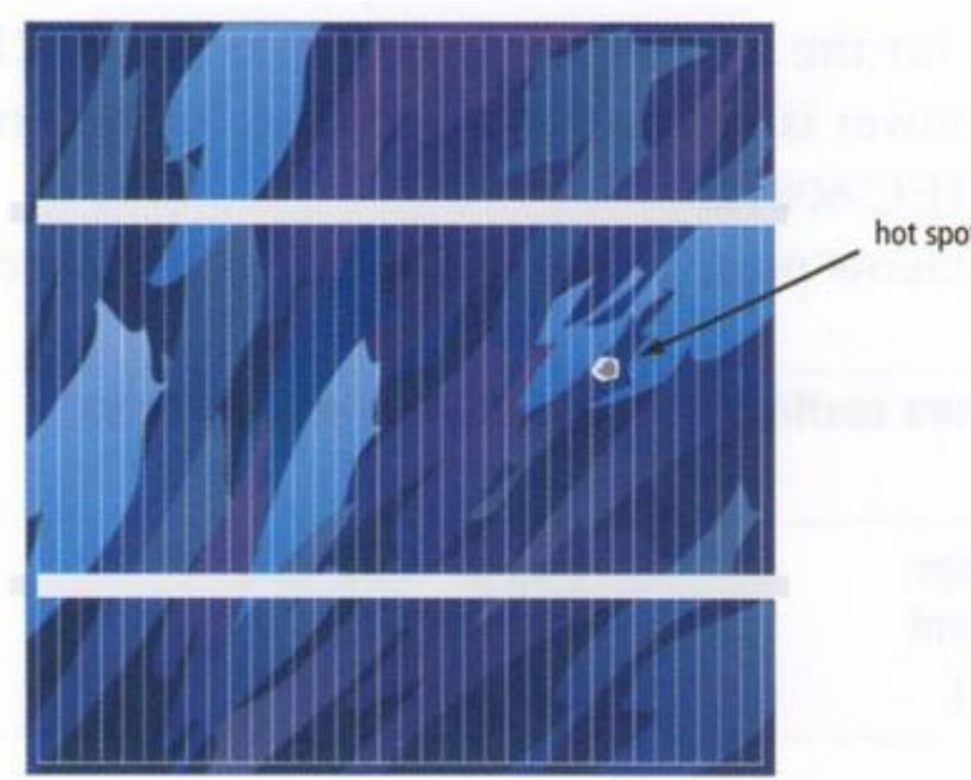
Electrical properties of PV cells and modules

Shading effects



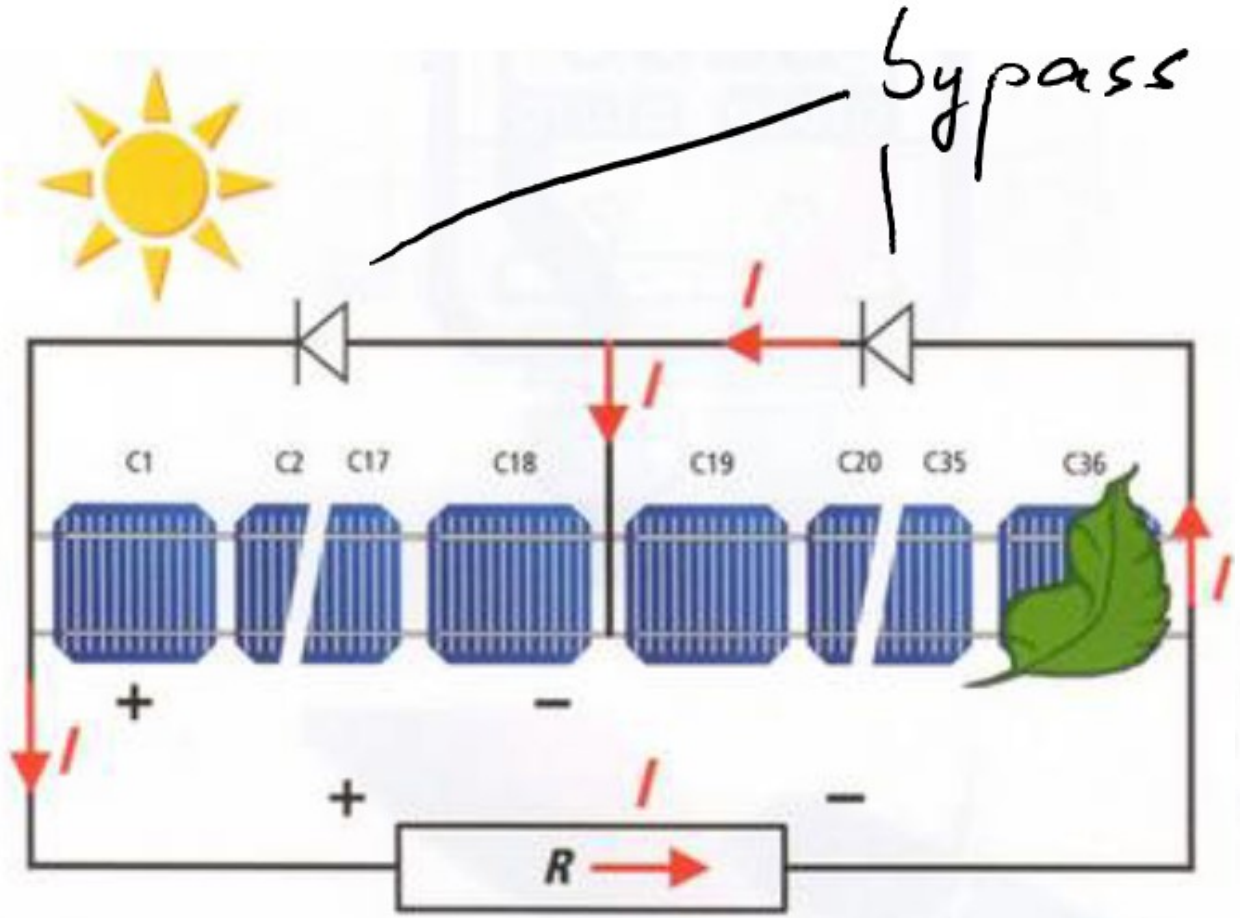
Source: R. Haselhuhn, in "Planning and Installing Photovoltaic Systems"

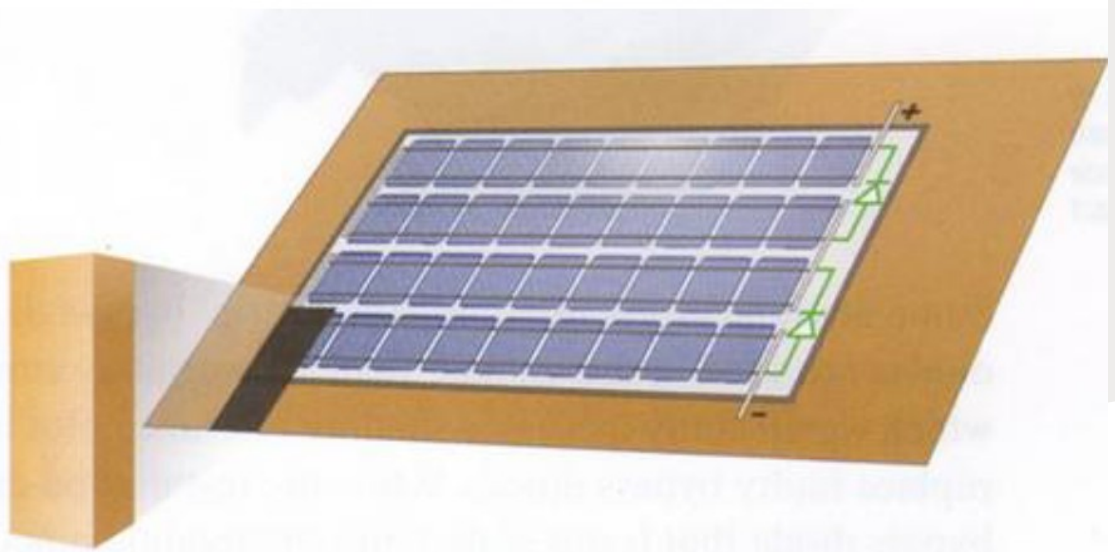
Heat due to shading can lead to hot spots and destroys the cell



Electrical properties of PV cells and modules

Protection against shading by bypass diodes





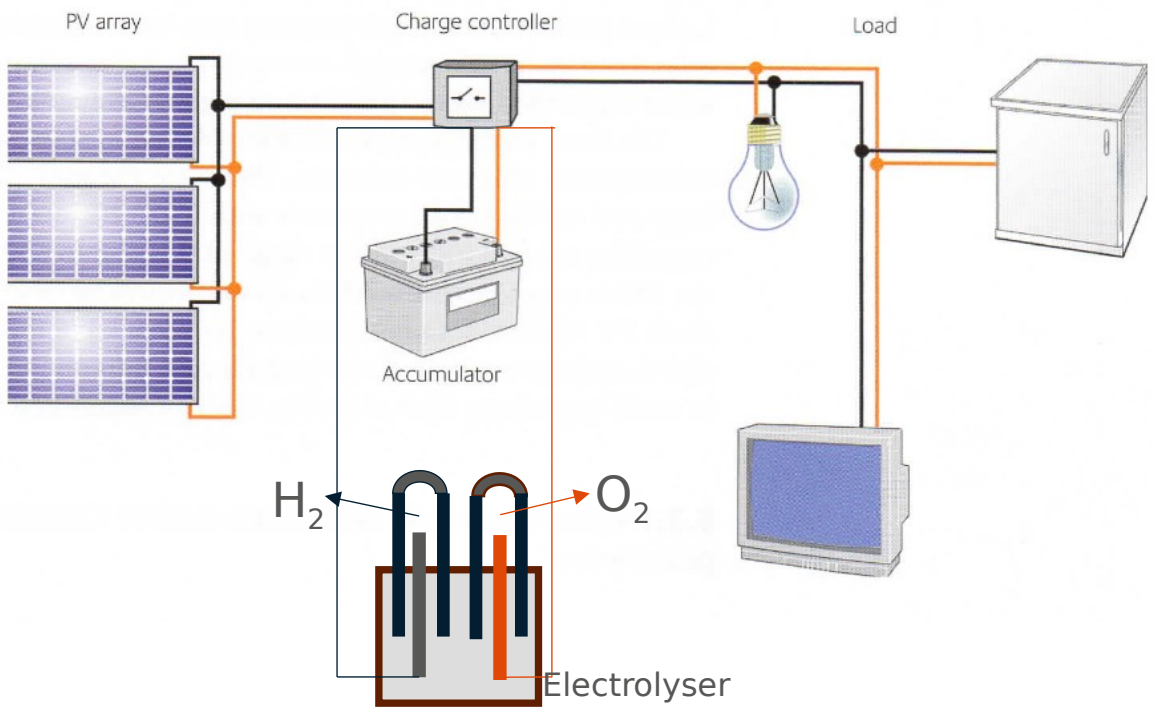
Types of Photovoltaic Installations

06

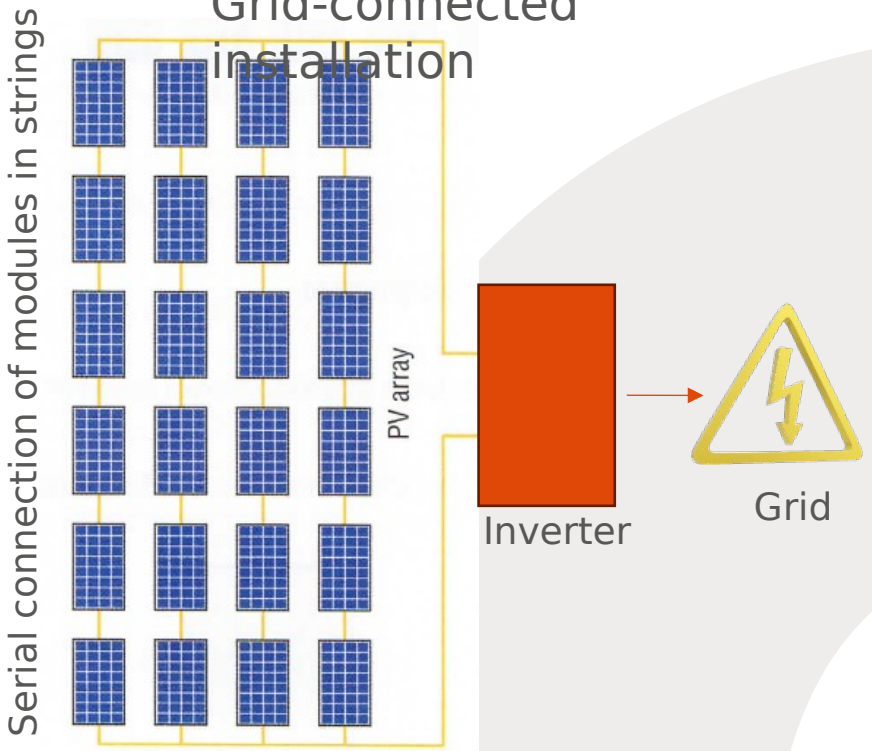
Types of PV installations

- In general, off-grid (stand alone) and grid-connected PV installations are distinguished, respectively. In both types, typically combinations of serial and parallel connection of modules are applied. Modules are serially connected in strings to obtain the necessary voltage and the different strings are connected parallel to obtain the amperage required.
- In the lhs picture below an off-grid arrangement consisting of PV array, charge controller, storage unit (battery, hydrogen electrolyser) and DC loads are shown. In case of 230 V AC loads, additionally an inverter is needed (DC-AC converter). The charge controller ensures that the PV modules always work at the MPP. If a battery is used for storage, additionally it protects the battery from overcharging and deep discharging. Instead of using batteries for storage, an electrolyser can be used to produce hydrogen.
- The rhs below shows an example of a grid-connected installation with a central inverter feeding the electric power from the PV array to the grid.

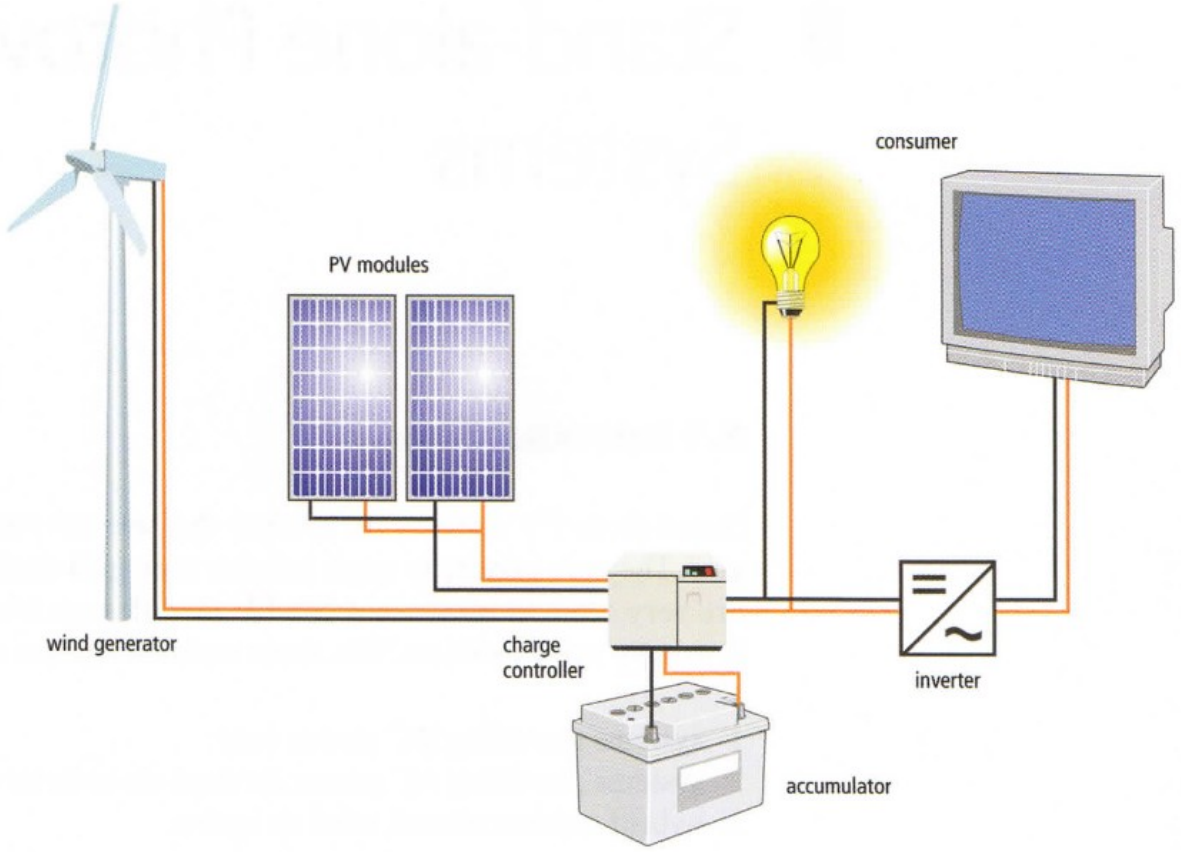
Off-grid installaton

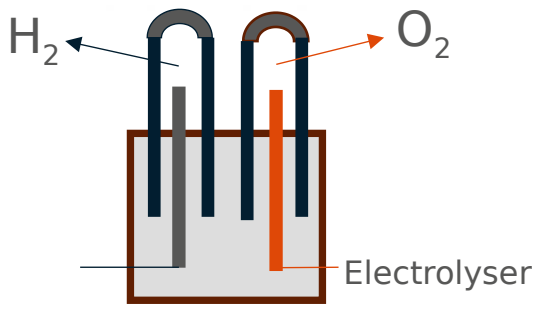


Grid-connected installation



Hybrid installation with PV and Wind





The hybrid charge controller has an AC input for wind and a DC input for PV